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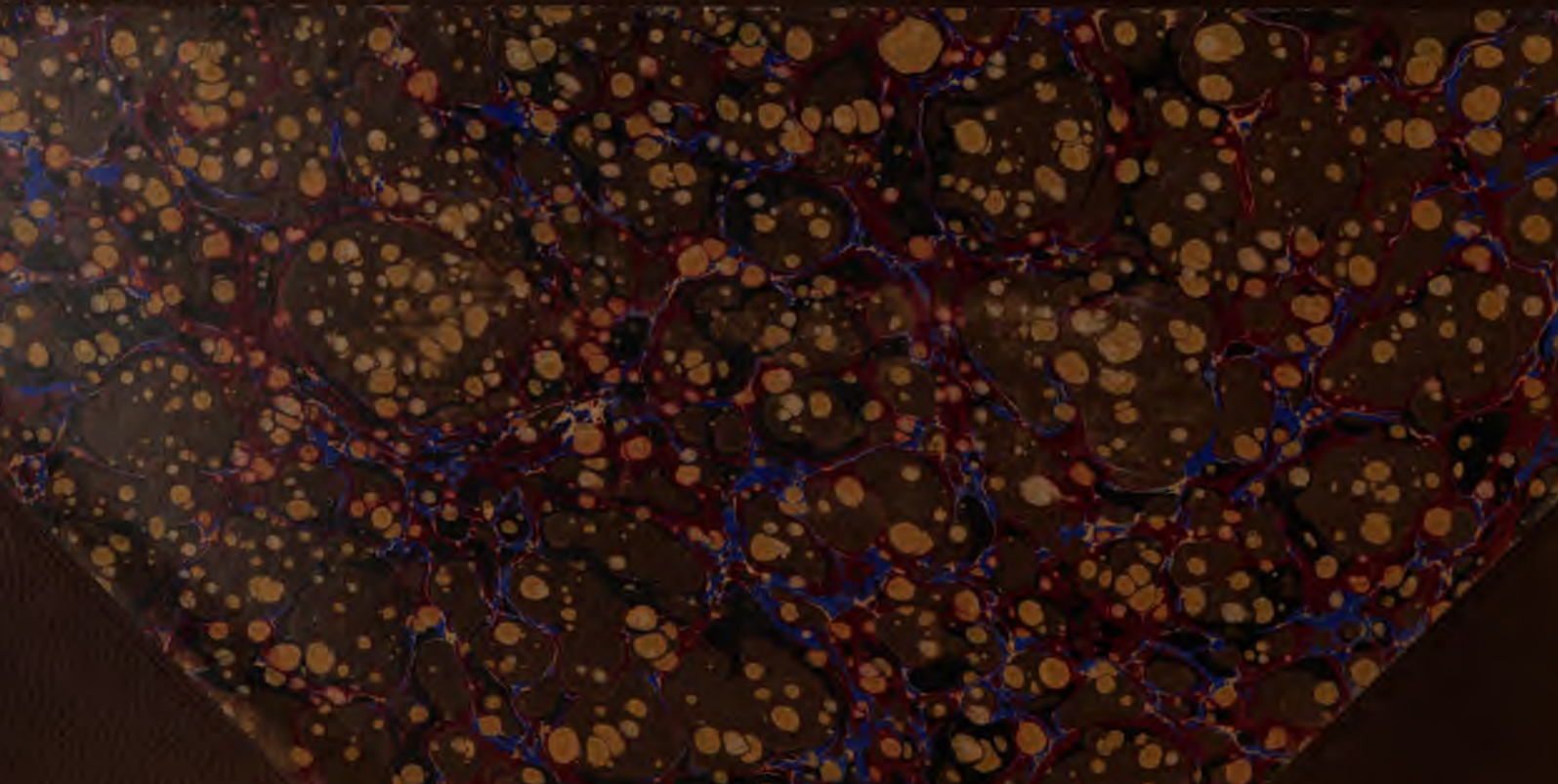

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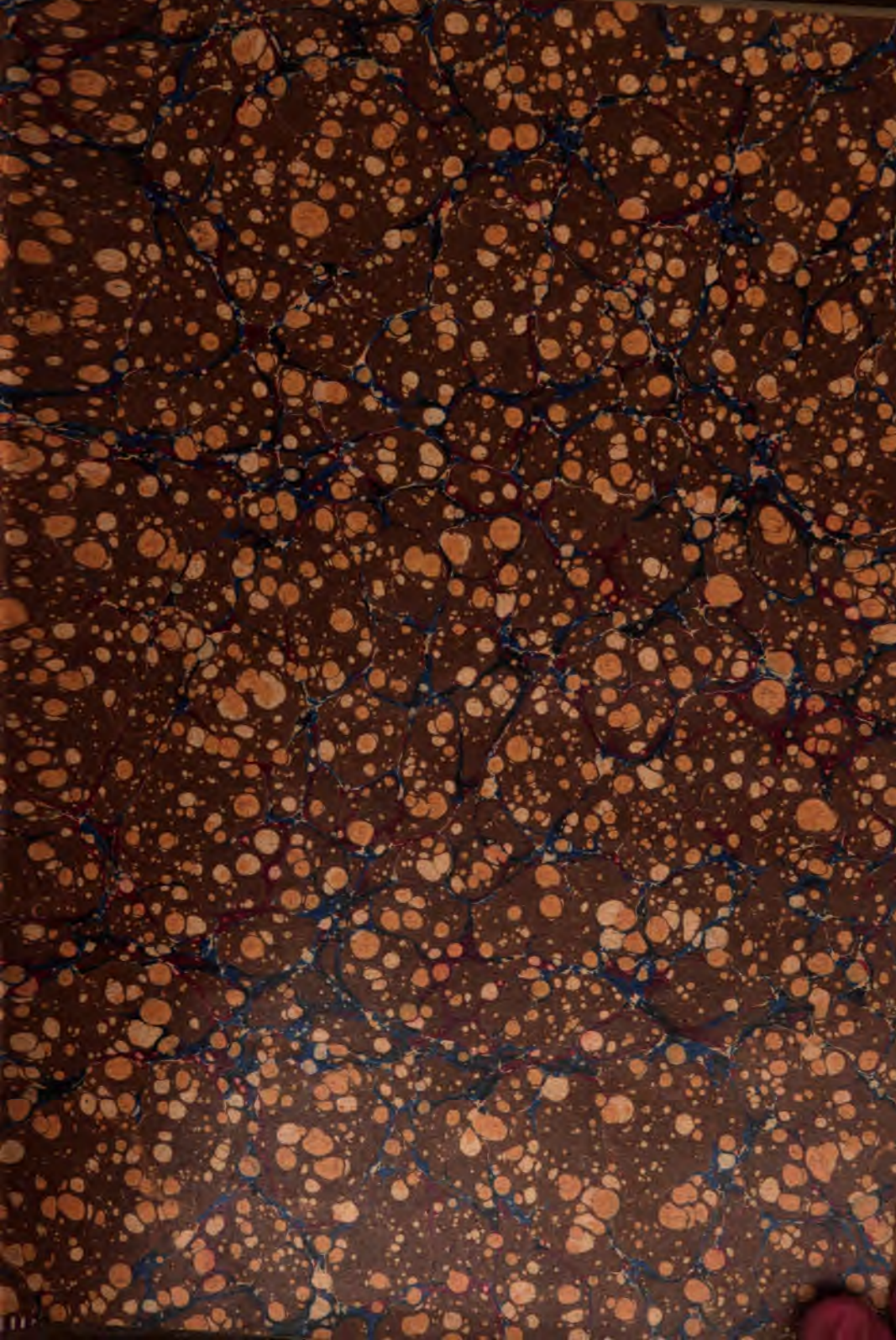

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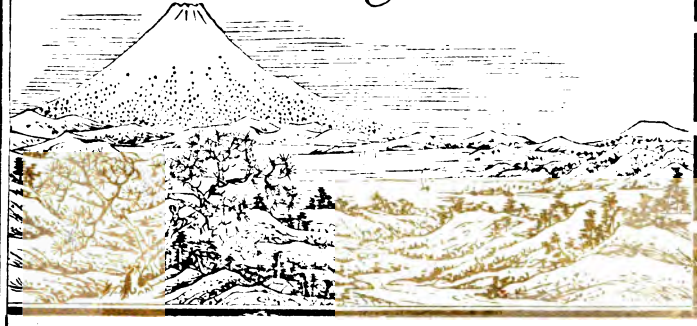

Vol. XII.

PRINTED AT THE OFFICE OF THE "JAPAN MAIL,"
YOKOHAMA.

TRANSACTIONS

OF THE

SEISMOLOGICAL SOCIETY

OF JAPAN.

VOL. XII., 1888.

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and 1835 immense flocks of sea birds flew inland, as if they had been alarmed by the commencement of some sub-oceanic disturbance, and before the last shock it is related that all the dogs escaped from the City of Talcahuano.

That the lower animals show signs of alarm at the time of a severe shaking is an observation hardly requiring explanation. If, on the contrary, it had been observed that they did not exhibit feelings of uneasiness an explanation might be necessary. The observations which do require an explanation are those where animals have shown a strange behaviour a short time *before* an earthquake, which so far as I can learn is usually 10 or 30 seconds in advance of the actual shaking.

The only explanation which I can offer for this phenomenon is that such animals are sensitive to small tremors which precede nearly all large earthquakes. Diagrams of earthquake motion showing these preliminary tremors, which have an amplitude of less than $\frac{1}{10}$ of a millimeter and are performed at the rate of six per second, have been published in the Transactions of this Society. If we were living on a hard, rocky formation the amplitude of these movements might be less and their frequency increased. If we are standing up, or down-stairs, or out of doors, we do not feel them, but if we are upstairs, sitting down, and all is quiet, they may occasionally be recognized. I have felt them, taken out my watch and noted the time 10 or 15 seconds before the actual earthquake came. On one occasion two of my friends, seated in an upstairs room, noticed them, while I myself, standing, endeavoured to detect them but failed. The problem before us may therefore be explained upon the assumption that certain of the lower animals are sensitive to small motions which we pass by unnoticed.

The alarm of intelligent animals like dogs and horses may be the result of their own experience, which has taught them that small tremors are premonitory of movements more alarming.

With pheasants, frogs, and geese, which latter animals have exhibited sensitiveness to anything unusual since the time they saved the Capitol, the alarm may be due solely to the tremors.

Cases where animals have exhibited strange behaviour several hours or days before an earthquake are probably accidental occurrences. In volcanic districts it has sometimes happened that before an earthquake certain gases have emanated from the earth, and where this has occurred the smaller animals have not only been alarmed but sometimes killed.

Occurrences like these are, however, extremely rare. Rossi mentions an instance where quantities of fish were killed by a gas eruption in the Tiber. On the morning of April 6th, 1874, at Follonica, the streets and roads were covered with dead rats and mice, in fact it seemed as if it had rained rats. The only explanation for the phenomena was that these animals had been destroyed by emanations of carbon diodide.

Discussion.

In the discussion which followed, Dr. C. G. Knott suggested as a reason why we do not feel slight tremors when standing, is that the points of contact with the earth are limited to our feet, and even these are more or less isolated by our boots, &c. Dr. Harrel gave an instance of a pony now in Tokio, showing symptoms of alarm at the time of a shaking. Professor Sekiya, who had kept pheasants to study their behaviour at the time of an earthquake, said that they had not yielded any definite results, inasmuch as they often screamed when there was no earthquake. Dr. Divers referred to a cockatoo in his possession which invariably screeched at the time of an earthquake.

THE GREAT EARTHQUAKE OF LISBON.

By E. J. Pereira.

[Read October 3rd, 1887.]

On the 1st November, 1755, at about 9.40 a.m., the town of Lisbon was almost entirely destroyed by one of the most appalling and calamitous earthquakes that ever occurred in Europe. This earthquake was followed by several other violent shocks, which caused a tremendous loss of life, calculated to have been between fifty and sixty thousand persons. The most extraordinary peculiarity connected with this event was that the weather, during ten days preceding the earthquake and the week following it, was remarkably clear and mild. It was also unusually dry for the time of the year.

Many accounts have been published of this memorable catastrophe, the effects of which were felt even as far as Germany and Ireland; but most of these accounts are filled with incidents of individual sufferings and hardships experienced during the catastrophe, rather than with any particulars of the phenomena observed during that extraordinary visitation.

There exists, however, a very rare pamphlet published in Lisbon in 1756 by a printer called Manoel Soares, and entitled: "A new and faithful account of the earthquake experienced in Lisbon and over Portugal on the 1st of November, 1755, with a few curious remarks and explanations of its causes," reproduced in the *Comercio de Portugal*, (October 31st, November 6th, 7th and 11th, 1886.) The author of this very interesting pamphlet gives a full description of all the circumstances preceding and following the earthquake, and informs us that, after the second shock a strong gale of wind

sprang up from the north-east, and a tidal wave swept along the coast. He also mentions that when the earthquake occurred, the weather was calm, the sky clear, the thermometer stood at 14 degrees (Reaumur) above freezing point, and the barometer marked 27 inches and 7 lines.

After giving his own theory on the causes of this extraordinary phenomenon, which he attributes to currents of air produced by subterranean explosions of condensed gas, the author proceeds to inform his readers of some remarkable observations made by him on that occasion, which I cannot better expound than by giving an abstract from the original narrative :—

The first shock, although preceded by a dreadful rumbling noise, was so slight that it scarcely frightened anybody, although it lasted over one minute. However, after an interval of from 30 to 40 seconds, the next shock came so violently, that houses began to crumble. The day turned dark owing to the thickness of the dust, and the tremors continued for a little over two minutes. After a lapse of less than a minute, the earthquake recommenced with great force. The houses, which had resisted the previous shocks fell with a terrible noise, the sun became dark, and the oscillating soil seemed to threaten utter destruction. The groans of the dying, the cries of thousands imploring divine mercy, the incessant shocks, and the darkness, all helped to increase the horror, fear, and tribulation. At last, after two or three minutes of the greatest suffering, the bustle subsided. The height of misery, however, had not yet been attained. Scarcely, says the author, had we begun to breathe more quietly, when a fresh shock came to foretell further disasters. A strong north-easterly gale sprang up ; and the sea rose suddenly and afterwards retired with equal haste. It carried away all it met, and then threw back all it had carried. The infuriated waves invaded the streets, squares, and gardens. Many of the people who sought refuge on the banks of the river were swept away by the sea without there being any one able to assist in saving

them. Those who jumped into the boats foundered with them; and the river Tagus, with its ebb and flow, was soon converted into a confused forest of entangled masts, and a horrible cemetery of floating corpses!

"Nothing can describe the deplorable condition in which the city of Lisbon was left. The town was first destroyed by the earthquake, then razed by fire, and pillaged by robbers. On the sites of wealthy palaces and mansions nothing remained but gloomy ruins and mounds of stones and rubbish.

"The first ten or twelve days after this terrible event, the tides had no regular course. Sometimes they were late, and at other times slow. There were at times seven and eight hours of high water, and then three or four hours of low water. During all this period the earth shook with more or less violence. On the 8th day at 5.30 a.m., the earth shook with fearful impetus, but the shock lasted very little time; the 15th day at 5 a.m. there was a severe shock; the 16th day at 3.30 p.m., the explosion was terrific. During the night of the 17th and 18th day a fearful underground noise was heard towards the north, followed by an earthquake; and on 8th December, between 11 and midday, all the people fled precipitately from their houses.

"On the 31st October the tide was two hours later than usual, and nearly two hours on 10th December. A pilot, having observed that the delay of the tide on 31st October was followed by such a tremendous earthquake, and noticing that the same thing occurred on the 10th December, went about the populous quarters of Lisbon, warning everybody not to remain under a roof that night, lest there might be an earthquake. This prediction turned out true; for on the 11th, at 4 a.m., the earth shook twice with great violence. A dreadful rumbling noise preceded these two explosions; but the duration of both shocks was not more than a minute and half. On the 21st of the same month, at 9 a.m., the earth trembled twice. The first shock, although severe, was followed by a

still more fearful explosion; and, although these movements lasted only one minute, they caused a good deal of destruction.

"As the earthquake of the 1st of November proceeded from south-west to north-east the sea followed the same direction; and this was the salvation of all the lower part of Lisbon; because, the waves breaking against the entrance of the river, they there lost their greatest force.

"Several ship captains, who were out at sea on the 1st of November, reported that at thirty, forty, and sixty leagues out, they had suddenly felt their ships jerk so violently that it seemed as if all the parts that composed them were going to pieces; and that they saw the guns jump on their carriages. The cause of this can be explained in the following way. The bottom of the sea is a continuation of the land; if this land is agitated it communicates its movement to the sea that covers it. The ships partake of this movement, because, floating in a fluid they balance a column of water equal to their mass; and the water moving with an irregular motion, the ship which forms part of the same fluid, follows the irregularity of the movements that agitate it.

"The disastrous effects of the earthquake of the 1st November were felt all over the kingdom of Portugal, but more especially in the province of Algrave, where the towns of Faro, Lagos, and Silves were completely destroyed, and Tavira, Albufeira, and Castro-Marim in greater part ruined.

"It is said that a portion of Lisbon Rock gave way, as also portions of the coast at Cascaes and Peniche.

"It has been remarked," continues the author, "that places near the sea-side have suffered more by these earthquakes than those inland. This observation has often and repeatedly been made; and it appears to me that the cause is this. Perhaps the quantity of inflammable matter deposited in the bowels of the earth is so disposed, that the mere contact of water can inflame it. When the sea rises higher, either during

high tides, or when the wind pushes it further, it may get introduced into various subterranean canals; and the water may thus penetrate where it never can without some such cause. I am persuaded that, in the same way as the movements of the moon have influence on the tides, so they may produce an equal influence on earthquakes and volcanoes; I have observed that the most violent explosions are always felt at syzygies and quadratures of the moon.

"I am also persuaded that the heat of the sun contributes towards the earthquakes that we are feeling daily. We find that the heat of the sun helps to inflame the materials which chemists mix in order to imitate the causes of volcanoes. What confirms me more than ever in this opinion are the repeated observations I have made that when a cloudy and rainy day is followed by a burning sun, there always occurs a violent explosion.

"I am convinced that the cause of so great a destruction of buildings on the 1st of November, was due to the strange character of the shock, which was at times vertical, and at times horizontal. In fact the movements were so contrary and opposed to each other that the strongest and thickest walls got separated, and crumbled. But although the shock at the time of the earthquake was dreadful, still I am sure it would have done less damage if the houses were built with more security. Unfortunately most of our houses have the following defects:—

"1.—The blocks of the angles or corners of the house are not in union with the walls, because they have not sufficient width or thickness.

"2.—On an equal level the stones have not an uniform height.

"3.—As the stones forming the lintel of the window, have not more width than the lintel, nor the thickness of the frame, they do not fit the wall, except by an angle which is in most cases roundish.

"4.—The walls are built with various sized stones, and the hollows are filled up with a bad mixture of clay, sand, and water.

"5.—The clay is allowed to cool, long before it is used, and it therefore gets dried and calcinated.

"6.—Very often the mortar is prepared, not with sand, but with the earth obtained from the foundations.

"7.—The sand used by our bricklayers is invariably sea-sand.

"8.—The clay obtained from the oven is prepared with salt water, by which process the saline particles mixing with the clay and sand prevent the walls from getting united and firm.

"In conclusion, the wood frame of the roof being always built without beams, the rafters lean against the wall itself; so that the weight of the roof and ceiling has the effect of a wedge which pushes the walls outwardly. At the commencement of an earthquake the walls get detached from the rafters, and the roof sinks; then the walls returning to their natural position meet the roof and, with the following oscillation, lose their equilibrium, and fall.

"It was noticed that large buildings suffered more than small ones, during the earthquake. For a reason easily understood this must always be the case. In the horizontal movement of the quake, all houses describe an arc, which is wider in proportion to the height of the house and its greater distance from the centre. This can be explained in the following way. Similar arcs are related to similar circles as circles are to their diameters.

"Diameters have between them the same proportion of rays. Therefore similar arcs have similar rays. The height of a house is the ray of a circle described by that house in its oscillation; consequently, the larger the arc the greater the ray, and the worse the damage. Moreover, similar velocities are like equal times; and the spaces being the arcs described by the roofs of the houses, the velocity is therefore greater on the

roof of houses; and it decreases towards its foundations. It is also greater in a high house than in a low one. Ruin is, for that reason, more imminent with large buildings.

"Another remarkable fact observed during the earthquake was that in the same street some houses were not in the least damaged, whereas others were completely destroyed.

"The only way in which this can be explained is by supposing that the underground vaults are raised with more violence in some places than in others, and that the direction of the effort depends on the horizontal or inclined position of the vault; so that it is from its extent, thickness, the nature of its formation, and the way in which the buildings are lined, that we are to account for their being in some places safe and in others completely ruined.

"In our history there are three remarkable periods relating to earthquakes. The first is the earthquake which occurred in Portugal in the year 1309; the second, the shocks and oscillations which did so much damage to Lisbon in 1531; and the third the disastrous earthquake of which we had such a sad experience in 1755. These three periods give me the idea of a hypothesis, which may appear very extravagant to many people, but which may not be without foundation. I am persuaded that between the years 1977 and 1985 there will be a great earthquake in Portugal.

"It has been observed that at Lima, a city in Peru, there is a formidable earthquake every sixty years. Why should not the same fact be applied to Portugal, in the history of which we find three seismic periods, with equal intervals of two hundred and twenty-two years.

"The following (says our author) are the most remarkable earthquakes that have occurred in Portugal, and more especially in its capital, the city of Lisbon: 22nd February, 1309, a terrible shock at daylight; 9th December, 1321, three very severe earthquakes; 24th August, 1356, the earth shook for 15 minutes and many houses were destroyed in Lisbon.

"7th February, 1531. Fearful shocks, causing many victims in Lisbon, and forcing people to live in the open air, for fear of being buried under the ruined houses. On the 26th of the same month there was a terrible shock in Lisbon, which was felt within a circle of seventy leagues. In the city about fifteen hundred houses were destroyed, killing scores of people. Churches were ruined, and ships sunk in the river. The shocks lasted several days; causing the Royal family and a large portion of the inhabitants to retire to the country in the neighbourhood.

"On the 28th January, 1551, an earthquake destroyed two hundred houses in Lisbon, killing over two thousand persons.

On the 7th June, 1575, at about noon, the land about Lisbon began to shake so severely that the inhabitants cleared out of their houses.

"In 1597, on 21st July, during an earthquake, the hill in Lisbon, known as St. Catherine's, sank and disappeared quite suddenly in the river.

"On the 28th July of the following year (1598) at 5.30 p.m., the people in Lisbon were startled by a smart shock, followed by two milder ones.

"26th October, 1699, severe earthquakes were felt in Lisbon, which continued intermittingly during the greater part of November.

"On the 26th of May, 1719, shortly before sunrise and during an eclipse of the moon, a fearful noise followed by an earthquake of three or four minutes' duration occurred in the southern part of Portugal. Another severe shock, on the 27th December, 1722, ruined many towns in the same part of the Kingdom.

On the 12th October, 1724, at 2.45 p.m., a very smart earthquake was felt, not only in Lisbon but all over the country; and finally the calamitous shock of the 1st November, 1755, of which the above account has been given, and which caused,

not only destruction and ruin to Lisbon, but carried desolation to many flourishing towns in its neighbourhood."

In concluding the abstract I have given of the pamphlet on the great earthquake, I may perhaps add that, since that memorable event, no extraordinary earthquake has visited Portugal beyond that of the 11th of November 1858, at 7 a.m.; the weather being at the time fine and clear. This shock, which lasted about 48 seconds, was preceded by a rumbling noise, and followed shortly after by a strong wind from the north-east. The damage done to the city of Lisbon was very trifling; but at Setubal, a town situated at the mouth of the river Sado, and distant some twelve miles from Lisbon, many houses were destroyed, and several persons were killed.

In the midst so many conflicting theories as to the origin or cause of earthquakes, it is interesting to find another obscure seismologist of the last century entertaining the very prevalent idea that earthquakes are produced by tidal action acting on the interior of the earth. This opinion, to a certain extent, coincides with one of the latest theories, which attributes the earthquakes in the Mediterranean to the melting of enormous masses of ice in the arctic regions. An event of that kind might to some extent affect the regularity of the tides, and this again, according to the view of the observer above quoted, might be the origin of serious convulsions of the soil near to the ocean. As to his hypothesis that there are periods of seismic action on the coast of Portugal occurring at equal intervals of two hundred years, it can only be founded on some such theory as that of the existence of a submarine volcano near the coast, which gets into activity every two centuries, and the explosions of which continue for several days or even months, but gradually decrease in violence until they entirely subside.

That the cause of many or most earthquakes lies under the sea, there is very little reason to doubt: in fact we know that earthquakes seldom occur very far inland, and generally pro-

duce the heaviest damage on or near the sea-coast. It is possible that enormous landslips occur under the sea, near to the land; and that these sub-marine landslips are the origin of seismic action. This, however, only future study and careful sounding in order to ascertain if frequent changes occur on the soil under the sea, will be the means of proving. The action of strong currents, in constantly undermining the soil, might produce landslips, which would not only cause a more or less violent concussion on the land in the vicinity; but might also create a tidal wave of more or less magnitude. That such landships have occurred near the coast of Portugal seems evident, from the fact that a big island existing in the time of Augustine, and mentioned in the Roman History, has disappeared, and its place is now occupied by the Berleugas Rocks, with very deep sea all round.

The landslips and avalanches in Switzerland and other mountainous regions have often produced earthquakes. Why should not landslips occurring in the submarine mountains and cliffs, where the pressure is so much greater than that of the atmosphere, produce the same effect as it does on the land above the sea, but with still more violent results?

However, this is merely a suggestion that I bring forth, leaving to others more competent than myself the task of deciding whether it can or cannot be admitted among the numerous theories on the origin or cause of earthquakes.

Discussion.

Mr. Milne, on rising, thanked the author of the paper for his valuable contribution to the historical section of Seismology. No earthquake which had ever occurred was better known or had been more written about than the Lisbon calamity of 1755. The sermons which had been written about this earthquake were exceedingly numerous, several of which, dating about 1756, he had pleasure in exhibiting. Notwithstanding all this, Mr. Pereira had acquainted them with some-

thing about the Lisbon catastrophe which they did not know before. These were the views of an anonymous author who was a spectator of the destruction. The most remarkable feature in many of the views held by this writer was that they were ahead of the time. What to most people in 1755 was a supernatural vistation were to the author whom Mr. Pereira had introduced to their notice, phenomena which might be explained by natural causes. One view he held was that shocks were more frequent at the syzygies, which is the time of spring tides. Somewhat similar views seem to have been held about the same time in Japan. In 1618, Richard Cocks says that in Japan it was thought that earthquakes were more frequent at the time of high water, the reason being that the rising tide shut air in cracks and caverns which in its endeavours to escape, shook the ground. In 1703, Georges Baglioli and Joseph Tolado suggested that there might be terrain tides produced by the action of the moon, but it was not until 1854 that this idea was discussed philosophically by M. F. Zantedeschi. The proof that earthquakes are really more frequent at certain phases of the moon than at others, is due to the labours of Professor Perrey, of Dijon. The differences in favour of certain seasons are, however, small. Thus between 1843 and 1872 Perrey found that earthquakes had been distributed as follows:—

At Syzygies	8,838
At Quadrature	8,410
At Perigee	3,290
At Apogee	3,015

In Mr. Milne's opinion these slight differences were hardly sufficient to establish a definite law. In many countries, as in Japan, the results of investigations are exactly the reverse of Perrey's result. Also with regard to earthquakes and the tide, Mr. Milne stated that he had found that there were 11 per cent. more earthquakes at low water than at high water. As to great sea waves or alteration in the level of the water in 1755 not having been produced by the same cause that pro-

duced the earthquake he was in great doubt. Great waves certainly have occurred when there have been no sensible earthquakes, but when we have earthquakes, originating in the ocean, it is only natural to conclude that there may be waves. The great difference in time between the shocks and the sea waves at the time of the Lisbon earthquake may be explained by the fact that the sea waves travel slowly and the earthwaves with great rapidity. In water the depth of the Atlantic the sea waves may have travelled at the rate of say 40 miles per hour while the earth waves may have travelled at the rate of 3 miles per second.

Taking these numbers as approximately true, then, if the Lisbon disturbances originated in the volcanic belt running north and south in the Atlantic, say at a distance of 800 miles off shore, the interval in time between the sea waves and the earth waves, must have been at least 2 hours, and in this way sea waves belonging to one disturbance may have been confused with disturbances which did not take place until 2 hours after their production.

In speaking of the destruction that occurred at Lisbon the marked deficiences in effect between that which happened in the low ground as compared with that upon the high ground had apparently been overlooked. The low ground in Lisbon, where destruction was the greatest, he was told, consisted of clay and soft material, while on the high ground where the destruction was relatively small, it was basalt or limestone.

Mr. Pereira confirmed the statement made by Mr. Milne that the greatest destruction caused by the Lisbon earthquake of 1755 was in the lower portion of the town. The so-called *Cidade Baixa* was totally ruined; whereas the buildings on the highest part of the town nearly all escaped destruction.

Dr. Kikuchi remarked that in the paper there was a statement about certain weather being premonitory of earthquakes. There is also a popular belief in Japan about dull, stifling, hot weather being a sign of earthquakes—a belief not justified by

scientific observations so far as he knew. But it is singular that there should be such an agreement (not grounded on a common *fact*, *i.e.* physical fact). Perhaps it is to be explained by a psychological fact or something of that kind. Dr. Kikuchi then said that he thought it might be interesting to some present to know that they had just missed the 33rd anniversary of the great Ansei earthquake by a day. Yesterday (2nd Oct.), (though the real date is the 2nd day of the 10th month of the 2nd year of Ansei), was held at Ekoin, near Ryogoku Bashi, a "Segaki" (a sort of public mass) for the souls of those who died by that terrible earthquake and the still more destructive fires which followed. All those bodies which were not claimed or identified were buried at Ekoin.

Prof. Sekiya said that the premonitory tremors which usually preceded the principal motion differed in their duration as observed in various destructive earthquakes. In the Lisbon earthquake of 1755 they learned from Mr. Pereira's paper that the fatal shock arrived a few minutes after the commencement. In the great Yedo earthquake of 1855, which devastated the city, the main destruction was completed with one blow. People scarcely felt any preliminary vibration. The duration of the Charlestown earthquake was nearly 40 sec.; the motion at first was moderate, but increased with great rapidity during the last 10 or 15 secs. In the Italian earthquake of Feb. 23 of the present year, the trembling began somewhat gently at first, but soon grew more and more marked, and then came a fearful shock. As to the sea waves which followed the shock of 1755, there were many similar cases in this country, and people who live near the coast in a shaky land like Japan should always keep in mind the danger of remaining near sea-shores at the time of great quakes.

The Chairman (Dr. C. G. Knott) said—The author of the pamphlet touched upon many of the points which are still subjects of discussion. Upon a few of these only I shall make any remark. The tidal phenomena, which are de-

scribed as accompaniments of the great Lisbon earthquake of 1755, are certainly very extraordinary. It would be well to search through contemporary literature for corroborative evidence; for we can hardly accept the simple statement of one man who probably got much of his information second-hand. In times of danger few people are capable of making accurate scientific observations. We have here tides described as occurring two hours later than usual on the days preceding certain of the heavy shocks. Such seeming regularity might be explained as due to temporary changes of level of the land; but the nature of the disturbance as described is too extraordinary to be accepted without reserve. The possible connection between tidal stresses and earthquakes is of necessity touched upon in rather vague terms by the author of the pamphlet. He adds, however, that he had observed that the most violent explosions are always felt at syzygies and quadratures of the moon. Observe, syzygies *and* quadratures; the very form of the statement suggests doubt. We should like to know on what special system of averages he established such a conclusion, and what range of time is expressed by the preposition "at." I am afraid there can be little true scientific basis for the conclusion.

The description of the seismic events which make up the great Lisbon earthquakes suggests a succession of explosions, probably at different centres—one might call it a train of explosions following the first shock and started by it in the seismically sensitive crust. The premonitory rumblings suggest a first origin at some distance; for when great shocks come suddenly without any previous symptoms, it is probably because of the nearness of the origin, in virtue of which the more rapidly-moving condensation wave has not time to gain appreciably upon the distortion waves. With regard to the suggestion made by Mr. Pereira that submarine landslips might be a cause of earthquakes, I should be inclined to think that such landslips were rather to be reckoned among the effects of seismic shocks. Submarine denudation plays quite an

insignificant part in the fashioning of the contour of ocean beds. There is lacking in such regions the needed variety of actions which in the case of subaërial deundation exists in the form of wind, rain, snows, frost, and running waters.

In conclusion, it is my pleasing duty to convey to Mr. Pereira the thanks of the Society for his valuable contribution to the historical side of earthquake literature.

MODERN FORMS OF PENDULUM SEISMOMETERS.

(THEIR DEVELOPMENT AND TESTS.)

By John Milne.

[Read October 3rd, 1887.]

Pendulum Seismometers are the oldest forms of seismometers employed for obtaining records on a stationary plate. In 1841 pendulums of this description were employed to record shocks in Scotland. The chief objections to these instruments are that they are not provided with any arrangement to magnify the motion of the earth, and that at the time of large earthquakes the value of the records are destroyed because the pendulums invariably swing. (See Experiments in Observational Seismology by J. Milne. Trans. Seismological Society, Vol. III., p. 12.) The first pendulum seismometer with a multiplying index is the one described and constructed by Dr. G. Wagener. (See Trans. Seismological Society, Vol. I., p. 54.) From Dr. Wagener's description of this instrument, it is clear that it was the inventor's intention to counteract any tendency of the pendulum bob to oscillate by the inertia of the multiplying index, and from his account of the instrument, owing to frictional resistances, or otherwise, if the pendulum was set in motion it quickly came to rest.

The essential portions of this instrument are illustrated in Fig. 1. *W.* is the main pendulum, at the base of which there is a long lever *s o p* acting as a multiplying index or "indicating pendulum." The short arm of this is *s o*, and the long arm *o p*. At *s* and *o* there are universal ball joints. *B o* moving with the earth and *s* being at rest, the lower end of *s o p* gives

a multiplied representation of the motion at *o*. As *s o* was 1 in., and *o p* 24 inches in the original instrument, it would appear that relative to *o* as a centre of percussion the centre of oscillation of the "indicating lever" was between *o* and *p*, and therefore when *o* moved to the right, *s* must receive an impulse to the right, and as the support of *w* received a displacement in a similar direction to *o*, the tendency of *w* to follow its point of support rather than being retarded in its motion would receive assistance. Its inventor argued otherwise. Notwithstanding this theoretical objection, the instrument did good service. It was the first where multiplying indices were used, the first where an attempt at compensation was introduced, and, although not fulfilling all the conditions required in this class of instrument, it was so suggestive that it may be regarded as the pioneer amongst modern pendulum seismographs.

Fig. 2 represents a pendulum seismograph described in the Transactions of the Seismological Society Vol. IV. p. 91. This instrument has done good service in Japan, and many of its records have been published. The improvements relative to instruments which preceded it are: 1st, the main pendulum is ring formed, and the steady point *s* is at its centre of inertia; 2nd, sliding pointers *o o* resting on a glass plate are used to render the pendulum dead beat; 3rd, by means of the ball *w* which is used as a universal joint, the centre of oscillation of *s w p* relative to *w* is above *w p*, and in this manner *s w p* rather than assisting *W* in following the movements of its point of support has a slight tendency to retard them. This important suggestion of loading *s w* originated with Mr. T. Gray. Later, Mr. Gray (Trans. Seis. Soc. Vol. III., p. 145) drew attention to the necessity of rendering an ordinary pendulum for small displacements absolutely astatic, and he suggested various means by which this might be accomplished.

In the same publication Vol. V., p. 89, Prof. Ewing described a duplex pendulum, a modified form of which he described in Vol. VI., p. 19. In this instrument an ordinary

pendulum is rendered astatic for small displacements by placing an inverted pendulum beneath it and so uniting the bobs of the two pendulums that any horizontal motion is common to both, and the jointed system so proportioned that neutral or feebly stable equilibrium is obtained.

The essential parts of this instrument are shown in Fig. 3, where W is the main pendulum, w the inverted pendulum connected with W by a ball joint and resting on a pivot at r, $o\,p$ the multiplying lever, receiving its motion through $B\,o$, there being at o a universal joint, and t the plate on which the records are written. If L is the length of the main pendulum W, and l the length of the inverted pendulum w, for astaticism or feebly neutral equilibrium $W\,l = w\,L$. An improved form of this instrument has been described by Prof. Sekiya. (Trans. Seis. Soc. Vol. VIII. p. 83.)

Although these instruments are, for seismometrical work, theoretically perfect, in practice such of them as I have had have presented certain objections, amongst which I may mention the following.

1. The difficulties of adjustment; 2. The limited size of diagram which can be obtained; 3. The difficulty in inserting and removing the smoked glass plates; and, 4, the fact that the pointer being cranked at its upper end does not give a satisfactory record in directions at right angles to the plane of the crank.

Fig. 4 illustrates an instrument which may be regarded as a modification of the old form shown in Fig. 2, where w has been increased in size and $s\,o$ in length, or it may be looked upon as similar to Fig. 3, with the stem of the inverted pendulum $w\,o$ prolonged downwards to become a pointer. The objection to this form of instrument is that there is considerable weight bearing upon the gimbals at o, and $o\,p$ to obtain the requisite multiplication has to be increased in proportion to $s\,o$. Notwithstanding this, a very satisfactory machine may be constructed about 2 ft. 3 in. in height, which on account of the

position of the pointer is more convenient to manipulate, and which yields records more satisfactory than any of the duplex pendulums which were previously in my possession.

A form that is still more compact than that shown in Fig. 4 in the one in Fig. 5 where the inverted pendulum resting on a pivot at o has its weight w which, as in the other instruments is adjustable, is above W. A prolongation of $w\ s\ o$ forms the writing lever $o\ p$. In this arrangement astaticism for small displacements is obtained when $\frac{w}{W} = \frac{p^2}{Ll}$, where $p = s\ o$, L the length of the main pendulum and l the length of the inverted pendulum.

The dimensions of a machine which I am now using (see Fig. 7) are as follows. Total height of tripod carrying W, which is suspended by three strings from a screw passing through a plate which can be moved horizontally, is 2 ft. 9 in. Side of triangular base, 2 ft. Height of triangular table, in the centre of which there is a hole crossed by the bar B, is 1 ft. 1 in., $s\ o = 1\frac{1}{2}$ in. W is a lead ring 7 in. diameter and $\frac{3}{4}$ in. thick. w is a brass disc $1\frac{3}{4}$ in. in diameter, and $\frac{3}{16}$ in. thick.

The lower end of a pointer is shown in Fig. 7; p is the end of the pointer carrying a fine glass tube g, through which a pin slides and is shown resting on the smoked glass plate t. The sliding pointer is used in preference to several other common forms, as experiment indicates that it writes with the least friction. t rests on the shelf m, hinged at o. When the wedge w which is attached to a pivotted handle is drawn back, then m is lowered so that the plate falls beneath the range of the sliding pointer, and the plate may be withdrawn.

NOTE.—Since writing the above, several machines similar to Fig. 7 have been made; amongst the rest there is one which only measures 6 × 7 in. It is enclosed in a crystal case and firms a useful ornament for the mantlepieces of all residents in an earthquake country.

TESTING PENDULUM SEISMOGRAPHS.

Several of the seismographs which have been described were tested by placing them on a small table which could be easily

shaken and comparing the diagram given of a shaking by a seismograph with a diagram of the actual motion of the table. The table was especially constructed with legs which were slightly flexible and loose. Beneath the centre of the table and extending downwards there was an ordinary seismograph pointer connected with the table by a ball joint, and, a short distance below, connected by a universal joint with a frame standing on the ground. This indicating pointer or lever gave a record on smoked glass 6.3 times larger than the motion of the table. All the instruments which were tested were placed immediately above this pointer and in similar positions. In the accompanying table the record of an instrument and the simultaneously obtained record of the actual motion of the table are placed side by side.

The instruments tested were :—

One of type 5, with *w s o* adjusted, first, so that the pendulum had a 4-second period, and second when it had a 2-second period.

Two of type 4. In one *w* was larger than in the other.

Two of type 3. This was an improved form of Ewing's duplex pendulum. (Trans. Seis. Soc. Vol. VIII. p. 83.) These instruments were lent to me by Professor S. Sekiya, and are similar to seismographs used by Professor Sekiya in his own laboratory. I believe the instruments to be as good as any of this type used in Japan.

I shall call the diagrams given by these instruments, numbers 1, 2, 3, 4, and 5. The records given by seismometers are marked S. while the records of the motion of the table are marked T.

Looking at records No. 1. (Instrument Fig. 7) it will be seen that for displacements of small range the record of the table and the record of the machine are practically absolutely identical, while for large movements where the diagrams are 54 millemeters in greatest length the deviations from the

actual motion of the table are very small. The diagrams are correct in form and size. In diagrams 2 and 3 (Instrument Fig. 4) the correctness is not so near as in No. 1, the errors, which, however, are only slight, being more marked with the smaller diagrams.

For diagrams No. 4 (Instrument Fig. 3), all that can be said is that the diagrams are correct in amplitude. In form they are barely recognizable as delineations of the movement of the table. The diagrams given are the best that could be obtained. The pendulum had but feeble stability, and there were no arrangements by which the stability could be increased.

The machine giving the diagrams No. 5 (also Instrument Fig. 3) was set on the shaking table by Professor Sekiya's assistant, who understood the instrument. Its stability was much greater than No. 4, it having a period of 3 seconds. One source of error in the diagrams was due to the pendulum invariably swinging for some time after the motion of the table had ceased.

The instrument shown in Fig. 7 is here described for the first time, and I am led to describe it on account of its simplicity, compactness, and the satisfactory character of its records.

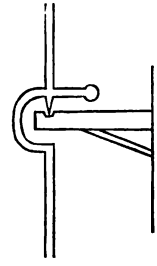
Its friction point and surfaces it will be observed are three in number. A sliding pointer, the point of a light secondary pendulum, and a ball joint.

In other instruments sources of frictional error are more numerous. Thus, in Fig. 3 there are no less than eight bearing-points and surfaces,—a writing point, the bearing point of a heavy secondary pendulum, two ball joints, and four points in a universal joint.

DISCUSSION.

Dr. Knott's remarks were as follows:—Professor Sekiya has pointed out what may be called a kinematical imperfection in Professor Milne's new form of Seismograph. The vertical rod, just below the heavy weight, has to rest on a fixed support, and is then continued down to form the

style which traces the motion on the usual smoked glass plate. To get past the horizontal bar which offers the needed support, the rod is expanded into an eye or ring through which the bar passes. Evidently there is here a danger that, by virtue of rotation of the rod about its own central axis, the sides of this ring expansion may come in contact with the bar, and so render valueless the tracery of the motion. This danger may be so far minimised by cutting away the one side of the ring expansion, and substituting a bracket for the bar, as shown in the diagram. By initially adjusting the rod so that the semi-circular bulge lies in the same plane with the fixed bracket, we render the chances of fouling much less than in the former case. Still, however, it is quite possible that a rotation of two right angles may occur, especially during a shock of some duration.



Theoretically, the following arrangement is kinematically perfect. A cross-piece ending in knife-edges is fixed perpendicularly to the vertical rod—as shown by *a b* in the diagrammatic sketch. This cross-piece rests on a circular ring, which in its turn rests by means of the knife-edges *c*, *d*, on fixed supports. *a b* is at right angles to *c d*; and the whole should be so arranged as to bring all the knife-edges into the same horizontal plane. In this way the point of intersection of the two lines of edges is a fixed point, and should be in the axis of the vertical rod. The co-planarity of the knife-edges is most easily effected by giving a suitable shape to the ring, making it dip at the points *a* and *b* as shown in Fig. 2. Such a shape of ring will also give slightly greater stability to the ring as resting on its own knife-edges. Dynamically of course, such an arrangement is not symmetrical; the rod and connec-

FIG. 1

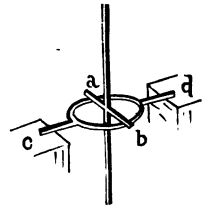
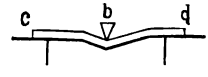


FIG. 2.



tions having less moment of inertia about the $a\,b$ axis than about the $c\,d$ axis. But the difference will be of very small account in the pendulum seismograph, in which the action of the heavy weight will completely mask all possible irregularities due to the distribution of other matter. The frictional effect of the knife-edges will be quite insignificant in the presence of other frictional constraints.

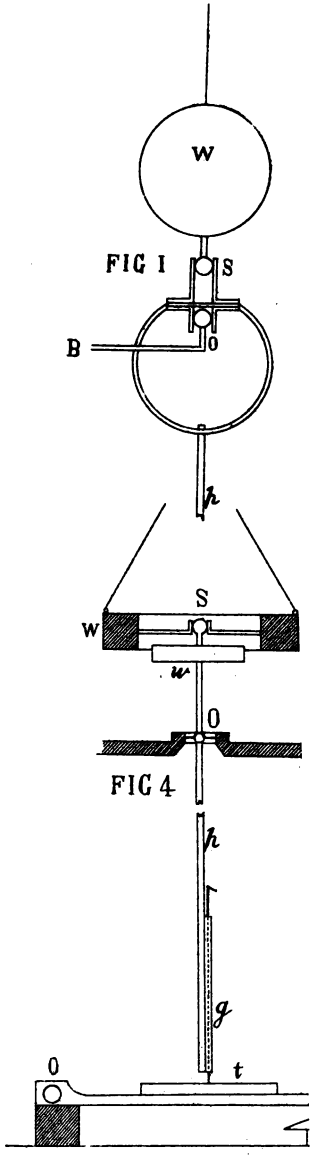
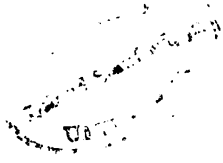


FIG I

FIG 4

FIG 6



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THE SONORA EARTHQUAKE OF MAY 3, 1887.

By T. Sterry Hunt, LL.D., F.R.S., & James Douglas, M.A.

(Read, at the request of the Authors, before the Seismological Society.)

On the afternoon of May 3, 1887, at 2.12 Pacific time (=120 W. of Greenwich), the first of a series of earthquake movements was felt in the State of Sonora and the adjacent parts of Mexico and the United States, over an area extending from El Paso in Texas on the east, to the river Colorado and the Gulf of California on the west, and from the State of Sinoloa on the south, as far north as Albuqerque in New Mexico, the extremes in both directions being over 500 miles. It was the fortune of the writers to be at the time at the great copper mining camp of Bisbee in Arizona, in a narrow gorge of the Mule Pass Mountains, about 5,300 feet above the sea, and near the border of Sonora. A violent tremor of the earth, including two sharp shocks, and lasting over ninety seconds, was succeeded at frequent intervals by many lesser movements in the next three days, and less frequently at least up to May 29. In this part of Arizona solid house-walls, of adobe or unburned brick, were cracked or overturned, while huge rocks in the steep mountain gorges rolled down, causing much damage. Fires, perhaps kindled by these in their course, appeared immediately afterwards in various wooded regions in Sonora and Arizona, giving rise to many false rumours of volcanic eruptions. The movement here seemed from south to north; the railroad track in one place near the frontier, running east and west, was displaced three inches to the north, while a chimney shaft, without being overturned, was turned violently around upon its base. The small town of Bavispe in the Sierra Madre in Sonora, was nearly destroyed, many people being wounded and forty-two killed. Opoto suf-

fered in a similar way, and Fronteras to a less extent. The district chiefly affected by the earthquake is, however, for the most part a desert, with some cattle ranches and mining stations.

Interesting studies were made by the authors in the valleys, or *mesas*, between the parallel mountain ridges in this region, both in San Pedro and Sulphur Spring Valleys. The latter, to the east of Bisbee, and stretching north and south about one hundred miles, is often eight or ten miles wide, and has its lower portion in Sonora. Though without a visible watercourse, water is there generally found at depths of from ten to forty feet in the numerous wells sunk at intervals to supply the needs of large herds of cattle. As described by many observers, the surface of this plain was visibly agitated by the first earthquake shock, so that persons were in some places thrown down by the heaving of the soil, which burst open with discharges of water, while the wells overflowed and were partially filled with sand. In the southern part of this valley, for about seven miles south from the Mexican frontier, the authors found the result of the undulatory movement of the soil apparent in great numbers of cracks and dislocations. For distances of several hundred feet, along some lines with a generally north and south course, vertical downthrows on one side of from one foot to two feet and more were seen, the depressed portion rising either gradually or by a vertical step to the original level. Branching, and in some cases intersecting, cracks were observed. These depressions were evidently connected with outbursts of sand and water, which, along cracks—marked by depressions on both sides, sometimes covered areas of many hundred square feet with layers a foot or more in depth, marked here and there by craters two feet or more in diameter, through which water had risen during the outburst of these mud volcanoes. The authors examined many of these phenomena in northern Sonora, and took photographs which were exhibited. They note that while the earthquake movements in the adjacent hills of Palæozoic strata had left no marks, the dislocation over many square miles in the valley would have sufficed to throw down buildings and to cause

great loss of life in an inhabited region. There are belived to be no evidences of previous earthquake disturbances in this region since its discovery by the Spainiards centuries ago.

From the published reports of commissioners named by the State of Sonora, it appears that the regions injured by the earthquake are in two nearly parallel north and south valleys in the district of Moctezuma, along the river Bavispe, a tributary of the Yaqui. The town of Bavispe itself, 1,500 souls, lies about seventy miles south of the American frontier and 110 miles south-east of Bisbee, Arizona, its elevation being 3,073 feet above the sea. Here forty-two persons were killed and twenty-five wounded. Bacerao, twenty miles farther south, also suffered much damage, and the estimate for property destroyed in this valley was 218,199 dollars. Opoto, Guasalas, Granados, Bacudebachio, and Nacovi lie in a lower valley about thirty miles west of the last, the elevation of Guasalas being only 1,720 feet above the sea. The loss of life was here confined to Opoto, where nine were killed and six wounded. The injury done to property in this valley was estimated at 78,151 dollars. In both regions are noticed the opening, in the arable lands, of numerous fissures, generally north or north-east in direction, from many of which water flowed abundantly. The river, thus supplied in a time of excessive drought, swelled to the volume usual in the rainy season of summer, a condition which lasted up the time of the report of Senor Liborio Vasquez, dated at Bavispe, May 29, 1887. The fields had become green and the river moist with prevailing fogs. A report concerning the region of Opoto mentions not less than seven volcanoes in the vicinity, which were seen burning for two days, but without any flow of lava, while that for the Bavispe region declares that no volcano had there been discovered. The authors incline to the belief that, as was the case in the San Jose mountains, and others examined by them along the borders of Arizona, the appearances of volcanoes near Opoto were due to forest fires.

THE GRAY-MILNE SEISMOGRAPH

AND OTHER INSTRUMENTS IN THE SEISMOLOGICAL LABORATORY AT THE IMPERIAL COLLEGE OF ENGINEERING, TOKIO.

By JOHN MILNE.

[Read November 29th, 1887.]

The following instruments were exhibited :—

1.—GRAY-MILNE SEISMOGRAPH.

The following description of the Gray-Milne Seismograph is almost entirely a reproduction of the original description given by Mr. Gray in the *Philosophical Magazine* (April, 1887). The diagrams are taken from the same source, but are slightly modified. A few additional notes are added at the end.

The new form of apparatus has for its object the determination of the same elements as have been already enumerated with reference to an instrument previously constructed by Messrs. Gray and Milne. Provision is, however, now made for the whole of the record being obtained on a fresh surface, and for any number of earthquakes which may occur within a limited period, say a week, being recorded on the same sheet. The record-receiver is kept continuously in motion at a very slow rate, and time is marked on it at regular intervals by means of a good clock; the object being to secure with perfect certainty that most important element in earthquake investigation—the time of occurrence of the disturbance. In the most complete form of the apparatus the record-receiving surface is a long ribbon of thin paper, which is gradully unwound from one supply drum on to another, which may be called the hauling-off drum, by means of a

weight or spring and a train of wheelwork. The speed is rendered uniform by taking the paper in its passage from the one drum to the other round a third drum, which is kept continuously in uniform motion by a train of clockwork and a suitable governor. A somewhat simpler arrangement is obtained by using a single drum covered with paper, or a smoked glass or metal cylinder, and giving to this cylinder a slow motion of translation in the direction of its axis, so that the record takes the form of a spiral line round it. As, however, the rate of motion must be such as to give the time of occurrence with fair accuracy within a second of time, it is difficult to obtain a good record on a cylinder of moderate size, which will extend over more than twelve hours with this arrangement. It is of course easy to adapt the apparatus to be used either way, if that were desirable; but the continuous ribbon of paper is so much the better form of receiving-surface that the description given in this paper, in so far as it refers to earthquakes, only includes that form. The spiral record has some advantages in apparatus adapted to record slow changes of level of the earth's surface; and it will be again referred to in that connection. For such purposes the rate of motion may be made excessively slow; and hence the records for a considerable length of time may be written on one sheet.

At the time of occurrence of an earthquake, the rate of motion of the paper is automatically greatly increased, and a siphon pointer is simultaneously set into vibration, and made to mark seconds of time on the ribbon, thus showing accurately the rate of motion at any instant. The actual rate of motion of the paper on the slow speed may be varied from about a quarter of an inch to an inch per minute, and on the fast speed from about 25 to 50 inches per minute, with the present form of instrument. This change of speed is generally obtained by including in the driving clockwork two governors, one of which can be automatically thrown out of gear, either electro-magnetically or mechanically. The

latter method has been found the best and the simplest in practice. The arrangement commonly used is described below, and need not be more particularly referred to here than in a general statement of the operations it is intended to perform. At the time of an earthquake three operations take place simultaneously. One is the introduction in train with the clockwork of an adjusting mechanism which is intended to readjust the starting apparatus, whatever that may be, so that it may be in readiness for another earthquake should that occur. Another is to throw out of gear the slow-speed governor, or, if that method is adopted, to work a change-wheel lever, so as to shorten the train between the driving power and the governor. A third is to throw the siphon pointer into action so as to cause it to mark time on the record sheet. It will thus be seen that the instrument is intended to be absolutely self-acting, so long as its supply of paper lasts and the driving mechanism continues to go. The supply-drum can take as much paper as is required in a week on the slow speed.

The record is made in ink by means of fine glass siphons, in very much the same manner as that which was introduced by Sir William Thomson in his siphon-recorder for submarine telegraph-cable work. This is extremely well adapted for the continuous ribbon method of working, and, besides, gives an excellent clear record which requires no further preparation before it is filed for reference; and, what is of great importance, the record is obtained with exceedingly little disturbance from friction at the marking-point.

The siphons which write the horizontal components of the motion are controlled by two pendulums, the suspending wires of which are held out of the vertical by horizontal struts terminating in knife-edges which rest against the bottoms of flat V-grooves fixed to a cast-iron pillar rigidly attached to the sole plate of the instrument. These pendulums, when set in vibration, describe cones, and hence they have been called

"conical pendulums." The degree of deflection from the vertical can be varied from about one and a half inches to a foot, by sliding the pendulum-bob along the strut. The strut is made in two pieces, so that a part of it can be removed when high sensibility is required, and in consequence the mass is used near the knife-edge. The bob of the pendulum is suspended by a fine platinum or steel wire from an arrangement which permits the suspending wire to be lengthened and shortened, and also allows the points of suspension to be put in such positions above the knife-edges as causes the struts to place themselves in positions at right angles to each other, and at the same time provides the means of adjusting their periods of free vibration to any desired length.*

It is of great importance in apparatus of this kind that the mass which, through its inertia, enables the record of the motion of the earth to be written, should be as far as possible from the knife-edge or point fixed to the earth; a long period of free vibration can thus be obtained, combined with considerable stability of position, while the greatest motion to which the knife-edge is likely to be subjected does not turn the strut through a large angle. If this latter condition be not provided for, the interpretation of the record becomes exceedingly difficult; and this difficulty is likely to be greatly increased by the mass acquiring oscillations in its own free period of such large angular amplitude that the direction of the component which is being recorded becomes a variable quantity.

The siphon which writes the vertical component of the motion is controlled by a compensated horizontal lever instrument, on the same principle as that introduced by the present writer and exhibited to the Seismological Society of Japan, and described in the Transactions of that Society, vol. i. part l, p. 48, and vol. iii. p. 140, and also in the *Philosophical*

* This pendulum is a modification of one designed by Mr. Gray in the beginning of 1880, in which the weight was supported by a thin wire in line with a rigid vertical axis fixed to the end of the strut and resting against bearings so as to keep the strut horizontal.

Magazine for September, 1881. This instrument consists of a horizontal lever carrying near one end a heavy mass, and provided at the other end with knife-edges in a line at right angles to the length of the lever. The lever is supported by two flat springs, acting, through a link, on a knife-edge attached to it at a point between the mass and the knife-edges before mentioned, which are by this means held up against the apex of inverted V-grooves rigidly fixed to the framework. In the form of this instrument previously described in this *Philosophical Magazine*, the supporting springs were of the ordinary spiral type; but in subsequent instruments two flat springs have been adopted, because for the same period of oscillation of the lever without compensation they give a more compact arrangement. These springs are now made of such variable breadth between the fixed and the free ends that, as they are supporting the lever, each part is equally bent. They may either be initially straight, and bent into a circular form when in use, or they may be initially set to a circular form and straight when in use. When the lever is supported in this way it has a fairly long period of free vibration; and this may be increased to any desired extent by means of a second pair of springs, which pull downwards on a light bar fixed vertically above the axis of motion of the lever. This second pair of springs, besides providing the necessary compensation for the positive stability of the lever and supporting-spring system, gives a ready means of obtaining a fine adjustment for bringing the lever to the horizontal position. This is accomplished either by giving to the points of attachment of the compensating springs a screw-adjustment so that they can be moved a short distance backward or forward, or by making the point of attachment of one spring a little in front of, and of the other a little behind, the vertical plane through the knife-edge. The lever can then be raised or lowered by increasing the pull on one spring and diminishing that on the other. Sir William Thomson has recently suggested to the writer that a

flat spring, which in its normal state is bent to such a curvature that it is brought straight by supporting a weight on its end, might be found a good arrangement for a vertical motion seismometer. This would certainly have considerable advantage in the way of simplicity, and with proper compensation applied, say to the index-lever, so as to lengthen the period, may be found very suitable. The only doubtful point seems to be whether the want of rigidity in the spring may not lead to false indications in the record due to the horizontal motions.

The application of a rigid horizontal lever, pivoted on knife-edges and supported by springs as a vertical-motion seismometer, was first described in the earlier of the two papers to the Seismological Society of Japan, quoted above. The advantage of this arrangement, as rendering it possible to obtain a long period of free vibration by placing the intermediate point of support below the line joining the other two, was also pointed out. The advantage obtained by the lever itself, without compensation, over an ordinary stretched string was more specifically pointed out in the other papers referred to; and a method of obtaining very perfect compensation, either for a lever or an ordinary spring arrangement, by means of a liquid was then given. The idea of increasing the period of a vibrating system by the addition, as it were, of negative stability, which was first brought forward in these papers, has been worked out in various ways; but the method described in this paper is the most perfect yet adopted. Its application to the ordinary pendulum was also brought forward and discussed at a subsequent meeting of the Sesimological Society of Japan.*

The apparatus above referred to for recording the horizontal components of the motion during an earthquake may, when properly adjusted, be used for registering minute tremors and slow changes of level of the earth's surface. It is, however,

* "On a Method of Compensating a Pendulum so as to make it Astatic," by Thomas Gray, Trans. Seis. Soc. Japan, vol. iii. p. 145.

absolutely necessary for such a purpose that friction of the different parts should be reduced to a minimum; and hence the siphons, or the marking-points when a smoked surface is used, are only brought for a few seconds at a time into contact with the paper, thus recording a series of dots close enough together to form practically a continuous line. Another method, which gives excellent results and is simple, has been much used by Professor Milne in Japan. It consists in passing from the point of the index, through the paper, to the drum, a series of sparks from an electric induction-coil. The sparks can be made to pass at regular intervals by a clockwork circuit-closing arrangement; and, by the perforations they leave, a record both of their position and the corresponding time is obtained.* This method is absolutely frictionless so far as the recording-point is concerned, and has the advantage that the sheet can afterwards be used as a stencil-plate for printing copies of the record. An ordinary simple pendulum, furnished with a very light vertical index of thin aluminum tube giving a multiplication of 200, has been for some time in use. The record of the position of the end of the index is taken on two strips of paper which are being slowly pulled along, in directions at right angles to each other, under it. The sparks perforate both sheets simultaneously, thus automatically breaking up the motion into two rectangular components. The details of some forms of apparatus for this purpose will form the subject of a separate communication.

Mechanical Details.

The record-receiver consists of a long ribbon of thin paper, about five inches broad, which is slowly wound from the drum *A*, situated behind the drum *C* (Plate fig. 1), on to the drum, *B*, by means of a train of clockwork driven by a spring or a weight of sufficient power to keep the

* This method of recording the motions of an index was used by Sir William Thomson in his "Spark Recorder." "Mathematical and Physical Papers," vol. ii. p. 168.

ribbon taut. The rate at which the paper is fed forward is governed by a second train of clockwork, driven by a separate weight and governed by means of two Thomson spring-governors. In gear with this train of wheelwork there is a third drum, *C*, round which the paper is taken as it passes from the drum *A* to the drum *B*. This drum is kept moving at a uniform rate, and serves to regulate the motion of the paper. The object of the double set of clockwork mechanism is to render the rate at which the paper is fed forward independent of the size of the coil on the drums *A* and *B*. The surface of the drum *C* is covered with several thicknesses of blotting-paper for the purpose of giving a soft surface for the siphons to write upon, and of preventing the ribbon blotting or adhering to the drum in consequence of ink passing through the paper. This blotting-pad is of some importance, because a cheap kind of thin paper is found to answer perfectly for the siphons to write upon. They move with less friction on a moderately rough surface and on paper which rapidly absorbs the ink. Under ordinary circumstances the paper is fed forward from a quarter of an inch to an inch per minute, this being kept up continuously for the purpose of allowing the magnitude and the time of occurrence of any disturbance, which is of sufficient amplitude to leave a record, to be accurately obtained. This obviates the unavoidable uncertainty which exists as to the action of any automatic contrivance designed to come into action at the time of the disturbance. The time of occurrence is obtained by causing the siphon, *D* (figs. 1 and 3), to mark equal intervals of time on the paper ribbon. The siphon is fixed to a light index-lever which is pivotted on the end of the lever, *E*, and the link, *F*. The lever *E* turns round an axis at *G*, and rests with its end in contact with the wheel, *H*, which is fixed to the end of the hour-spindle of the clock, *K* (fig. 1). As each tooth of the wheel *H* passes the end of the lever *E* a mark is made on the paper, and the end of the hour is distinguished by putting a larger or a double tooth at that part of the wheel.

The time at which an earthquake has occurred can thus be found by measuring the distance of the record of the disturbance from the last time-mark, then counting the number of intervals from the last hour-mark, and then the number of hours to a known point. It is convenient to mark the hour once or twice a day on the paper, so as to save trouble in the reckoning should an earthquake occur.

The ordinary rate of motion is much too slow for the record to show the motions of the earth in detail; and, as has been already stated, this is obtained by automatically increasing the speed at the commencement of the shock. The arrangement for doing this is shown at *Q* (fig. 1), and is also illustrated diagrammatically in fig. 2. Referring to the diagram, *a* and *b* represent two levers, which are pivoted at *c* and *d* respectively. On the right-hand end of the lever, *b*, a ball, *e*, is fixed, and the weight of this is counterpoised by another ball, *f*, which rests on a rocking platform, *g*, pivotted on the other end of the lever. Opposite the end of the rocking platform, *g*, and fixed to the end of the lever, *a*, there is another platform, *h*, which receives the ball, *f*, when it rolls off the platform, *g*. The ball is prevented from rolling sideways by a light spring, *i i*, fixed to the sides of the platforms. On the end of the lever, *a*, or on another lever connected with it, the end of the spindle of the wheel, *j*, is supported. This wheel is in gear with the pinion, *k*, which is on the shaft of the most distant of the two governors from the driving-power. The ball, *f*, is so adjusted over the pivot of the rocking platform, *g*, that an exceedingly slight disturbance causes it to roll forward on to *h*, tilting *g* over, and at the same time pushing down the end of *a* and raising the wheel *j* out of gear with the pinion *k*, thus allowing the clockwork to run on without the governor which regulates the slow speed. The rate of motion then rapidly increases until the second governor acquires sufficient velocity to control the speed, after which the paper moves forward at a rapid but uniform rate. In order to again reduce the speed after a sufficient interval has elapsed, the rolling forward of the ball

f, allows the unbalanced weight of *e* to bring a wheel, *l*, on the spindle of which a "snail," *m*, is fixed into gear with the pinion, *n*, which forms part of the clockwork mechanism. The spindle of *l* rests on a spring, *o*, which is adjusted so as to push the lower part of the "snail" just into contact with a pin, *p*, fixed in the lever *b*. The weight of *e*, acting through the pin *p* on the "snail," deflects the spring, *o*, and brings the wheel, *l*, into gear with the pinion *n*. The "snail" is then gradually moved round and raises the ball, *e*, and the end of the lever, *b*, at the same time lowering the rocking platform, *g*. After this has proceeded so far as to cause the platform *g* to come below the lever of *h* the ball rolls back to its original position; and, as the "snail" moves round, the platforms are gradually raised to their original positions, the wheel *j* again comes into gear with the pinion *k*, and the speed is reduced. The wheel, *l*, remains in gear with the pinion *n* for a short time after the speed is reduced, so as to allow the final adjustment in position of the platform *g* and the ball *f* to be made gently. After this is accomplished a hollow in *m* allows the spring *o* to push the wheel *l* out of gear, and everything is left in readiness for the next disturbance.

In order to obtain the rate at which the paper is moving at any instant during the transition period between the slow and the quick speed, the movement of the lever *a* allows a wire forming the tail piece of *D* (Fig. 3) to fall until a pin on a forked lever touches the seconds wheel *S*. The siphon therefore records both the long and short time intervals.

One of the "conical pendulums" used for actuating the siphons which record the two horizontal components of the motion is illustrated in plan in fig. 4, and in elevation in fig. 5. It consists of a thin brass cylinder *r*, filled with lead, and held deflected by a light tubular strut, *s*, furnished with a knife-edge at *t*, which rests against the bottom of a vertical V-groove fixed to the support *u*. The weight of the pendulum-bob and strut is supported by a thin wire, *v*, attached in

the lower end to a stirrup, w, pivoted at x a little below and in front of the centre of gravity of r, and taken at the upper end over a small wheel, y, to a drum, z, round which the wire may be wound so as to adjust the level of the strut, s. The position of the pivot, x, is so arranged that the knife-edge at t has little or no tendency to rise or fall, no matter at what part of the strut the cylinder r may be clamped. The wheel y is provided with adjusting screws, a_1 and b_1, by means of which the top of the wire can be placed vertically above the knife-edge, or as much in front of or behind that point as may be necessary to make the period of free vibration of the pendulum have any desired length. A light aluminium lever, c_1, is hinged to the strut s at d_1, and is provided at its outer end with a small hollow steel cone, e_1, which may be placed over one or other of a series of sharp points, f_1, fixed to the vertical arm of the cranked lever, g_1. The lever g_1 turns round a horizontal axis at h_1 in bearings fixed to the ink-well, i_1, and the vertical arm is hinged at j_1, so as to be free to turn in a direction at right angles to the plane of the crank. A siphon, k_1, is fixed to the horizontal arm of the lever g_1, and, drawing ink from the well, i_1, writes a continuous line on the paper ribbon. The horizontal arm of the lever g_1 is made very flexible in a horizontal direction, and besides can be turned round a vertical axis to such an extent as allow the pressure of the point of the siphon on the paper to be adjusted until it is only sufficient to give a record.

The horizontal-lever pendulum used for actuating the siphon which writes the vertical motion is illustrated diagrammatically in fig. 6. It consists of a horizontal lever, l_1, carrying at one end a cylindrical weight m_1, and free to turn round knife-edges, n_1, fixed to the other end of the lever. The lever is supported in a horizonal position by two flat springs, clearly shown in fig. 1, and indicated at o_1, fig. 6. A light aluminium index, p_1, pivotted at q_1, and connected by a thin wire or thread to the end of the lever l_1, carries a fine siphon, r_1, which rests with one end in the ink-well, s_1, and

the other end touching the surface of the paper. The end of the index is weighted sufficiently to cause it to follow the motions of the lever. This arrangement gives a period of free vibration of about two seconds in the actual instrument; and in order to increase this period a second set of springs, indicated at t_1, are made to act on knife-edges, u_1, fixed vertically above n_1, so as to add negative stability to the arrangement. When the lever is deflected downwards the pull on the supporting spring is increased, but at the same time the knife-edge u_1 comes in front of the vertical plane through n_1; and, since the lower point of attachment of the compensating spring t_1 is far below n_1, a couple is introduced which compensates for the greater upward force. The same is the case in the reverse order, when the lever is deflected upwards. Hence, if the pull exerted by t, and the other conditions mentioned below be properly adjusted, the horizontal lever may be made to have any desired period of free oscillation. In actual practice some positive stability must be given to the lever in order that its position of equilibrium may be definite; but its period may be made so great that, even if oscillations of considerable amplitude in its own period are set up, they will be so slow compared with those of the earthquake, that the undulating line so drawn will still be practically straight, so far as the earthquake record is concerned. In order to insure good compensation, the condition must be fulfilled that the rate of variation of the compensating couple is always the same as that of the supporting couple. If this be not the case, the pendulum must either be left with excessive positive stability for small deflections, or it will be continually liable to become unstable by the compensating couple becoming too great when the deflection exceeds a certain limit. In the present instance, let the modulus of the supporting spring be M, the arm at which it acts a; let the modulus of the compensating spring be M_1, and the distance between n_1 and u_1 be a_1. Then for a deflection of the lever equal to θ we have, on the supposition that the length of the

supporting spring and link is great compared with a_1, for the return couple $Ma^2 \cos\theta \sin\theta - M_1 a_1^2 \cos\theta \sin\theta - M_1\beta \sin\theta$, where $\beta + a_1$ is the total elongation of the spring for the horizontal position of the lever. Now our condition necessitates β being either zero or negative; and in order to keep within this condition the length of the unstretched spring and link are made to reach a little above n_1, and the height of u_1 is made adjustable, so that $M_1 a_1^2$ can be adjusted to be as near Ma^2 as may be desired.

NOTES.—In making siphons glass fibres ought to be selected which have been broken at right angles to their length. These broken ends may be made smooth by taking a bundle of fibres between the finger and thumb and gently rubbing them on a brass plate covered with a little fine emery and water. Another plan which suggests itself is to bed the end of the fibres in Canada balsam, from which the turpentine has been driven off by heat, and allow the same to harden. After grinding on the brass plate the Canada balsam may be removed by alcohol. The fibres are bent by holding them over the glowing end of a pencil-like stick made of charcoal powder and rice paste. The short writing end of the siphon is formed first, and it ought to be slightly inclined in the direction of motion of the paper. They are fixed on the aluminium stems with parafine, the holders or stems being heated with a hot wire. The ink, which may be fed to the ink holders by a pipette, is made from water and a blue anyline dye. It ought to be filtered.

The paper may be readily wound back upon the roll from which it was fed by turning the same by hand, first having removed nearly all the weights from the cord on the right hand side and turned the pointers back from the paper. All the weights on the right side must be removed before taking out the cylinder on which the paper is wound.

A form of multiplying pointer which works satisfactorily is shown in fig. 7. In this figure s is a cross section of the

strut *s* shown in fig. 5 near to the weight *r*. The lower end of a light bell crank lever *l*, pivotted at *o*, rests against this. The end of this is connected by the thread *t* with the writing pointer *k*, which is pivotted at *m*. In one direction the writing pointer moves by the influence of gravity. As the greatest acceleration of earthquake motion which we are likely to experience is less than *g*, the arrangement promises to continue to yield satisfactory results.

When adjusted for working see that all pivots connected with the writing levers turn easily, but they must not have the slightest lateral looseness. The left hand double cord requires 28 lbs. and the right hand cord from 8 to 14 lbs. as driving weights. They require a fall of about 4 ft. 6 in.

Automatic Tremor Recorder.

This instrument, since it was described in Vol. XI. of the Society's Transactions, has been slightly modified. It now consists of a simple pendulum furnished with an aluminium pointer giving a multiplication of 200. At intervals of five minutes, sparks from an induction coil pass from the point of the index and perforate two bands of paper moving at right angles. As shown in the above-mentioned volume the movements of this instrument appear still to accompany the following conditions:—

1. It almost always records tremors when heavy winds are blowing in Tokio.

2. It almost always records tremors when heavy winds are blowing behind the mountains at a distance of 60 to 150 miles, although in Tokio and on the surrounding plain it may be absolutely calm.

The writer regards the instrument as having greater interest for the Meteorologist than for the Seismologist.

Milne's Duplex Pendulum Seismograph.

The instrument exhibited only differed from the instrument described in Vol. XII., by embodying the improvement

suggested by Dr. C. G. Knott, and more refinements in workmanship and construction.

Thus far it has worked with more satisfaction than any other instrument giving statical records.

An example of one of the diagrams given by this instrument is here reproduced. It represents a tolerably severe shock, which occurred on September 5th. The object in reproduction is partly to show the clearness in definition of the diagram and partly on account of the peculiarity of some of the movements which it will be seen are nearly circular.

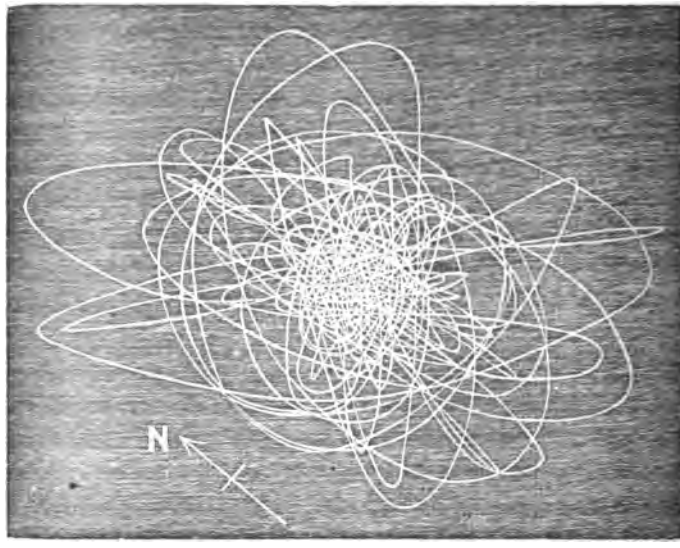
In order to separate some of these vibrations most of which in all instruments giving statical records are confusedly superimposed upon each other, a record receiving apparatus carrying a long plate of smoked glass is being arranged, so that the plate of smoked glass, after having received two or three vibrations drops out of contact with the recording index. After this it is moved a short distance horizontally and then moved vertically upwards to again touch the pointer and then receive two or three of the succeeding vibrations. This operation is repeated about 12 times, so that the total motion of the ground will be recorded in twelve parts and the confusion resulting from superposition be in this way avoided.

A Seismograph for Large Motions.

For recording large motions any ordinary seismograph recording without multiplication may be used. The one at present employed by the author consists of a plate and ball seismograph recording by means of a pencil sliding in a tube upon a sheet of paper. The position of the pencil is at the centre of inertia of the upper movable plate. (See *Phil. Mag.* Nov. 1881.)

To complete these instruments a seismograph for vertical motion writing on a stationary plate and seismographs for horizontal and vertical motion writing on moving surfaces are required.

THE EARTHQUAKE OF SEPTEMBER 3RD, 1887, AS RECORDED BY MILNE'S PENDULUM SEISMOGRAPH.



MULTIPLICATION = 6.

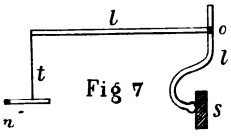
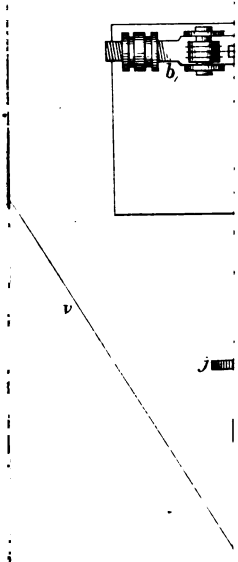
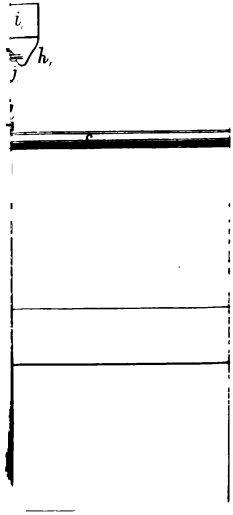


Fig 7





INSTRUCTIONS FOR SETTING UP AND USING THE GRAY-MILNE SEISMOGRAPH.

(SUPPLEMENTARY TO THE PREVIOUS DESCRIPTION.)

BY T. GRAY.

The instrument should be mounted with its sole-plate level on a substantial foundation, such as a stone pillar built up from the rock if it is near the surface or deep into the ground, if the foundation is soft. In the latter case a heavy log of wood sunk deep, with its length vertical, and firmly packed will do. The foundation pillar should not be high and should be so rigid that its own free vibrations have a very short period. It will generally be found convenient to pass the driving cord of the clockwork under pulleys fixed to the foundation and then over pulleys hung from or fixed to, the ceiling of the room in which the instrument is placed. A good arrangement is to place the weights at the side walls of the room leading cords to them by means of pulleys.

PAPER.—The paper drums should now be mounted as shown in the description and the top screw of the drum carrying the paper made just light enough to keep the paper stretched. A weight of about 10lbs. should be hung on the cord which keeps the paper taut and (when driving on a double cord) about 28lbs. on the driving train. A specimen of paper suitable for the purpose is sent out with the seismograph. If a heavier paper is used the length will be correspondingly diminished. The surface of the paper should not be very smooth, as very smooth paper retards the motion of the siphon by capillary action on the ink. Ordinary thin printer's unlaid paper suits well for the purpose.

GOVERNORS AND SPEED.—The governors should be adjusted to give the required speed. It is not advisable to reduce the slow speed below one third of an inch per minute, because if the speed be too low, the time of occurrence of any disturbance cannot be obtained with sufficient accurracy and the inking of siphons is apt to be too rapid. The governor is altered by screwing the balls nearer to or further from the side of the cylindrical box by turning the central nuts which turn a right and left handed screw and move both balls at once.

PENDULUMS, VERTICAL MOTION.—The pendulums are to be placed in the position shown in the illustration. The lever of the vertical motion one is brought to the horizontal position by adjusting the weight to the proper position on the lever. This can be readily done by slackening the clamp screw at the end of the weight then sliding the weight into position and fixing it by tightening the screw. The link of the compensating spiral spring should reach (when the spring is unstretched) a little above the knife edge. After adjusting it to this position by the screw at the bottom of the spring, they should be hooked on as shown. The point of the lever which remains steady during a sudden vertical movement of the earth is almost exactly the centre of the weight. The magnification is adjusted by changing the position where the link is attached to the siphon lever.

HORIZONTAL MOTION.—The horizontal struts should be placed in position with the knife edge resting against the bottom of the *V*, and the wire then hooked on to the weight. The weight has then to be raised or lowered until the knife edge bears along its whole length. This can be readily tested by feeling if the strut rocks over a point. The position of the strut, the period of oscillation, and the magnification of the record may then be adjusted in the manner described in the paper. The numbers stamped on the side of the strut indicate the ratio of the motion of the steel cone to the motion of the earth when the side of the weight nearest the knife edge is at

the mark. The graduations on the vertical arms of the siphon levers indicate the position of the top of the sliding clamp for magnifications 2, 3, 4, 5, and 10, the weight being supposed at the graduation marked 1 on the strut.

SIPHONS.—The siphons are made of thin glass tube, a supply of which should be sent with the instrument, but which can be easily made by heating a piece of $\frac{1}{4}$ inch or $\frac{3}{8}$ inch soft glass tubing (ordinary German glass tubing does well) in a blow-pipe flame and drawing it quickly out to the proper thickness. The siphons may be bent to the proper shape by means of the burning point of a carbon crayon, but it is, after a little practice, more easily done by means of a minute *horizontal* gas flame. The part to be bent is held close to the flame and the tube simply allowed to bend in the proper direction by its own weight. The ends are then cut to the proper length by holding the tube against a soft pad such as the point of the thumb, and drawing the edge of a sharp hard knife across it and then breaking it at the scratch. The end which touches the paper should be flat and smooth. It may most easily be smoothed by holding it in the small flame until it is red hot. When the siphon is too thick, and in consequence inks too quickly, it should be narrowed by heating it sufficiently at the point to allow it to become slightly narrowed. Care should be taken that the siphon is not so fine that it is unable to supply ink for the high speed. A siphon which writes a good full line when the paper is moving at about $\frac{1}{4}$ inch to $\frac{1}{2}$ inch per minute will write a fine but perfectly clear line when the paper is moving at 30 inches per minute. The siphons should be fixed to the levers with soft wax such as bees wax which, when fixing the siphon, may be melted by holding a hot wire against the backs of the lever.

CHANGE-SPEED MECHANISM.—This will probably be understood from the illustration and description, but one or two adjustments may be mentioned. There is a stop screw extending from the lever which changes the wheels upwards

which may be screwed up or down. The lower that screw is put, the sooner will the speed change *back* from fast to slow, *and it should be so low that the change takes place early enough to prevent the mechanism which adjusts the ball shooting out of gear at the same time, as this is apt to throw forward the ball again.* The final adjustment of the ball should be made on the slow speed. The delicacy of the starter is adjusted by the screw which presses against the spring at the back of the rocking platform.

INK.—The most convenient ink to use is a solution of aniline; this need not be strong, and it will be found most convenient to make up a stock bottle of such a strength as would suit well for an ordinary writing fluid. Care should be taken that the siphons dip well into the ink wells, but that they do not touch the bottom at any part of the range of motion of the lever.

NOTE ON THE SOUND PHENOMENA OF EARTHQUAKES.

By John Milne.

[Read January 26th 1887.]

1.—General Character of the Sounds.

Many observers who have experienced heavy earthquakes have given an account of the sounds which have preceded, accompanied, or occurred subsequent to the disturbance. Some compare these sounds to subterranean thunder, others to the rattling of chains, others to the escape of steam. Some compare what they heard to an explosion, to the rumbling of a heavy waggon or to the rattle of musketry.

In short the sound phenomena of earthquakes appear to be as variable in their character as the earthquakes themselves.

Old writers called these disturbances in the air, airquakes. The following are a few examples of such disturbances.

A correspondent of the *Gentleman's Magazine* of 1750 describing an earthquake felt in Lincolnshire on August 23rd of that year, says: "suddenly there came a sound from the earth as of a rushing mighty wind and it shook all the house with everything that was therein."—[*Gent. Mag.*, XX. p. 456]. A writer on the earthquake of New England in 1727 says that the accompanying sound as described by many, was like that produced by carts and coaches rolling over pavements, or shooting out loads of stones. He himself thinks that it was a "*sonus sui generis*," and there is no describing it.—[*Phil. Trans.* XXXIX.] The sounds which accompanied the Owen's Valley Earthquake of 1872, are said to have been more like the crackling and grinding of rocks

under tension than to explosions of detonating gases.—[*Am. Jour. Sci.* IV. 1872.] In a description of the Jamaica Earthquake of 1692 the sound which foreran or immediately accompanied the shocks is said to have been like that produced by putting the tongue to the top of the mouth and pronouncing *hur-r-r-r-r.*

The New England Earthquake of November 18th, 1755, was preceded for about one minute by a roaring sound.—[*Phil. Trans.* L.]

A sharp earthquake felt on January 30th, 1739, at Halifax in Yorkshire is described as ending with a "hizzing, hollow report, and quivering of all things on the surface."—[*Gent. Mag.*, 1739.] The sounds which accompanied the London Earthquake of February 8th, 1749, are described by various observers as being like thunder,—like the falling of heavy bodies,—as an explosion produced by the blowing up of a mine—as a rushing noise—like 10,000 cannon—a dull sound —the rumbling of a cart.—[*Gent. Mag.*, XXIII. 1753.]

It is probable that the nature of the sounds which are heard depend in a large measure on the position of the observer relatively to the origin, to the intensity of the disturbance, and the nature of the rocks through which the disturbance is propagated.

In a description of the earthquakes which shook Maestricht in 1751, we read that when the shocks were slight the preceding noise was like that of a cart deeply loaded, but when they were strong they resembled the sound of a coach rolling swiftly. —[*Gent. Mag.*, XXVII. p. 508.]

From the account of an earthquake which on October 23rd, 1858, shook New York, we see that observers differently situated described the sound phenomena which they heard differently. At Buffalo the sound is said to have been like that produced by a multitude of carriages rapidly drawn underground or the dull sonnd produced by dumping material. At Toronto and Lockport the sound also was rumbling.

At Fredonia the noise was sharp as if produced by the falling together of pieces of furniture. At Erie the sound is described as having been like that of heavy waggons passing over frozen ground, &c.—[*Am. Jour. Sci.* XXVI. 1858.] No sound was heard to accompany the Neapolitan Earthquake of 1857 excepting in a limited area near its centre.

That the area over which sound is heard is chiefly confined to the neighbourhood of the origin is common to many earthquakes. Humbolt tells us that the great shock of the earthquake of Riobamba (4th February, 1797), which is probably the most terrible phenomena of its kind of which we have records, was not accompanied by any sound whatever.

The tremendous noise (el gran ruido) heard beneath Quito and Ibarra occurred twenty minutes after the destruction at Riobamba.—[*Humb. Cosmos.* I., p. 203.]

In a like manner fifteen minutes after the earthquake of Lima and Callao (October 28th, 1746) a subterranean noise like a thunder-clap was heard at Truxillo.—[*Humb. Cosmos.* I., p. 203.] The occurrence of sounds *after* a shaking has been felt, are exceptional, and it is not unlikely that they are independent phenomena.

Of subterranean sounds like those which accompany or precede earthquakes, occurring in earthquake regions, we have numerous examples.

On April 30th, 1812, a noise resembling that of thunder was heard, unaccompanied by an earthquake, in the valley of the Orinoco. It extended over an area of 9,200 square miles. At the same time the volcano of S. Vincent in the Antilles commenced to erupt.—[*Humb. Cosmos.* I. p. 204.]

In the valley of Visp in 1855 and 1856, and even up to 1861, sounds unaccompanied by earthquakes were heard.—[*Am. Jour. Sci.* XXXVII. p. 1.]

A remarkable instance of uninterrupted subterranean noise unaccompanied by earthquakes is one which continued for

about a month in Guanaxuato, commencing about midnight on January 9th, 1784. The district over which it was heard was only a few miles in area and it died out gradually as it had begun. The sounds were like slow rolling thunder, interrupted with quick claps.

Almost all the inhabitants were seized with a terror which caused them to leave the city. Humbolt tells us that when the terror was at its height the magistrates issued stringent measures punishing the flight of a wealthy family by a fine of 1,000 piastres and that of a poor family with two months' imprisonment, all fugitives being brought back by the militia.—[*Humb. Cosmos.* Vol. I., p. 205.] These underground noises or *bramidos*, Fuchs says, are common in Nicaragua and Guatemala, where heavy thunderings will sometimes continue for weeks.

The noises which are attendent on earthquakes seem in the majority of cases to have *preceded* the shaking of the ground as was the case for instance in the Lisbon Earthquake of 1755.

In the Tokio seismic area, sounds accompanying earthquakes are rare. Although the author has observed many earthquakes when sounds are said to have been heard, it has only been once during a period of several years that he can say that he distinctly heard a sound. This was on March 11th, 1881, when a sound between a hissing and rumbling, was heard. Other instances have come before the author's notice where residents in Tokio have heard a rushing noise before an earthquake, but not a single instance where it has been observed after the disturbance.

One simple explanation of this phenomena, for a large city like Tokio, situated on alluvium through which we know that a shock may sometimes travel slowly, is that a disturbance reaching one side of the city, by shaking shutters and other loose objects may create a rattling or roaring sound which will cross to the opposite side of the city at a quicker rate than the motion is propagated through the soil. From my own

experience, however, the character of the noise is hardly that which would be expected to originate from a cause like the one just suggested.

Noises which will not admit of an explanation like the above inasmuch as they occur in country districts are common in certain portions of Japan, as for instance at Kamaishi 120 miles N.N.E. from Tokio.

This place is situated on the sea coast at the mouth of a narrow valley bounded by steep hills running back inland. Almost all the shocks at this place are heralded by a rumbling roar which it is said have sometimes lasted two minutes before the shaking commences. A noticeable point which has been remarked upon is that the greater the noise the less has been the shock, a fact which we may remark is paralleled by explosions in mines. Sometimes there are rumblings without any shocks.

In Yamaguchi Ken in the South of Japan some years ago during a period of unusual seismic activity, phenomena similar to those at Kamaishi were observed. And to this might be added the phenomena which occurred so recently in connection with the destructive shocks at Agram.

The nearest parallel to these explosive noises appears to be the throbbing and mutterings of a geyser like those which may so often he heard at the well known geyser in Iceland, where probably owing to the sudden evolution and condensation of steam, sounds and shakings are produced, often preceding the final pulse which causes the eruption. In a few instances the sound which accompanies an earthquake appears to have been transmitted to great distances. Some writers affirm that the rumblings which have been heard in mines have been more intense than those which were heard upon the surface. The earthquake of March 15th, 1835, which took place at St. Martha, in Columbia, was accompanied by detonations which were heard over an area of 350 miles.

A curious fact mentioned by Fuchs in connection with these sounds is that during the earthquakes at Brussa the vertical

shocks were not accompanied by sounds whilst the horizonal shocks were accompanied with noises. This observation it must be observed is contradictory to many other observations, as for instance those of Signor Abella of Manila, who in 1881 when seeking for the origin of the disturbances which had so severely shaken the province of Neuva Viscaya, arrived at the conclusion that where vertical motion had occurred which was above the origin, it had been simultaneously accompanied with sounds. The farther he receded from this origin, however, the greater became the interval between the motion and the sound.

Cause of Sounds.

On account of the want of accuracy and detail in the various observations which have been made with respect to the phenomena which have been described, it appears as yet impossible to assign for them an originating cause which shall be free from criticism. It has been suggested that certain of the sounds are the result of disturbance on the surface by the shaking of buildings and other objects—noises like detonation and thunder may possibly be due to explosions of steam—noises with a metallic ring, a grinding, whistling, or rattling, Fuchs suggests may be due to the friction between dislocated portions of the earth crust.

Mallet attributes the origin of the Neapolitan Earthquake in 1857 to the inrushing of steam into a fissure which in consequence was rent open to the right and left to form a cavity. During the rending, rushing rolling sounds were produced which, however, varied as might be expected with the positions of the various observers.

To these explanations another might be added founded on some of the recent observations of earthquakes, which show that the stronger shocks are preceded by a series of rapidly recurring tremors. These tremors as recorded by a seismograph commence with a frequency of about 6 per second but become slower before the shock takes place. They extend over an

interval of time closely corresponding with the interval of time by which sounds usually precede earthquakes. From General Abbot's experiments it would seem that still smaller tremors precede those which are recorded by seismographs. These small motions, although in every probability felt by some of the lower animals like pheasants, which may be often heard to scream before a shock, are usually unnoticed.

If we admit that motions of this description have a period of over 16 per second we see the possibility of rocks emitting a musical note.

A remark of Dolemieu when describing the Calabrian Earthquake of 1783 bears upon this point. He says that in the granite regions the sound was heard before the shock was felt, but in the alluvial plains the reverse was the case.

The explanation of this may be that the sound was only produced on the granite district, and that this after it reached the boundaries of the alluvium being so longer produced, it travelled through the air at a rate less than the motion through the soil.

In Japan also it may be remarked that the regions where sound accompanies earthquakes consist of hard plutonic and metamorphic rocks, whereas areas like the Tokio plain where sounds are but seldom heard, consist of alluvium.

The sounds emitted by the vibrations of glass rods, and the banks of musical sand in the Sinai Peninsula have a relation to this question.

One of these banks, described by Col. H. S. Palmer, R.E., is about 200 feet high and 80 yards wide. It is situated about 5 miles north of Tor. By wind, heat, passing travellers, and other causes, the sand gradually rolls down the surface of the bank in thin waves producing a deep swelling vibratory moan gradually rising to a dull roar. It may sometimes be likened to the noise produced by the rushing of air into the mouth of an empty metal flask. The sand which is quartzoze, gives

out the greatest sound when heated. Similar phenomena have been observed near Cabul and on the plains of Arequipa. [Report of British Association 1871, p. 188.]

The fact that miners underground have heard these sounds as if they were above their heads, whilst those on the surface thought the sounds came from the earth, is a fact tending to support the suggestion here advanced.—[*Phil. Trans.* XLIX., p. 546.] Viz., that the majority of earthquake sounds are produced by short period surface vibrations of the earth and these vibrations are portions of and continuous with the earthquake that accompanies the sound.

Use of Sound Observation.

When underground noises precede earthquakes, as they usually do, these phenomena at once become timely warnings of approaching danger. Instances of this will be quoted further on.

Professor J. Henry, in a note upon the seismic disturbances in North Carolina, remarks that if an area is being depressed the tension of the rocks would cause deep-seated cracks with attendent noises, whereas where the land is rising these would be near the surface. [*Ann. Rep. Smithsonian Inst.* 1874, p. 254.]

Subterranean noises might therefore possibly indicate depression, whilst noises near the surface would indicate elevation. From the duration of a sound and from its character as observed at different stations, important deductions may be made with regard to the area from which an earthquake originates.

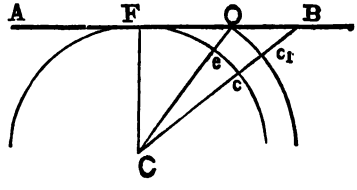
The principles which guide us in such investigations are as follows:—

First, let us assume that *the sounds originated at the origin of the earthquake and were transmitted to the surrounding districts through the air.* And secondly, that the time at which the sound was heard at a number of stations

round the origin was also known. If we also know the difference in time between the sound and shock at the different stations we have the means of increasing the methods of calculation. With these we are in the same position to determine the origin of a shock, assuming it to originate from a point, as we are when we have time observations at several stations upon disturbances on the land or in the ocean. (See Earthquakes, by J. Milne, p. 200-208. International Scientific Series.)

One great assistance is knowing the velocity with which sound is transmitted through the air. If, however, from the form of our isoseismals or curves of equal effect, or from other reasons we are led to the supposition that the disturbance originated from a fissure certain modifications must be introduced in the calculations.

For instance let us take the case of a fissure which by an explosive effort is rent open simultaneously along its length. In such a case observers situated on a line bisecting such a fissure at right angles would have a single sound, the duration of which would be shorter the further the observer was removed from the origin. Observers situated to the right or left of this bisecting line would hear a sound lasting over an interval taken for sound to travel the difference of distance between the nearest point and the farthest point on the fissure from the observers' station.



Thus, if *A B* represents a fissure which is rent open simultaneously along its length, the duration of the sound produced by the rending as heard at *C* would be equal to the time taken by sound to travel the distance *C B*—*C F* or *B c*. Another

supposition which may be made is that the fissure is rent open to the right and left from a central point *O*. To take a general case, let the observer be situated at some eccentric point *C*. From centre *C* describe two arcs one passing through *O* and the other through *F*, the nearest point on the fissure to the observer at *C*. If the interval taken to rend the fissure from *O* to *F* is greater than the time taken for sound to travel the distance *Oe*, then the duration of the sound will equal the time taken for sound to travel from *B* to c_1. If this interval is smaller than the time taken to travel through the distance *Oe*, then the duration of the sound is equal to the time taken to travel the distance *B c* plus the time taken to rend the fissure between the points *F* and *B*.

When we have a large number of observations on the duration and nature of sounds which are heard at the time of an earthquake the value of these observations must be very great. If the tremors which so often precede a large shock are produced by a rending action during the formation of a fissure, observations on their duration as experienced at different stations might be employed in a manner similar to the sound phenomena.

If it should be definitely shown that in a given case the sound phenomena were produced by the *transit* of the disturbance, these latter remarks will be inapplicable.

The sound phenomena of earthquakes form a branch of seismology which has hitherto been greatly overlooked, the investigation of which will undoubtedly yet be made to yield facts of great importance.

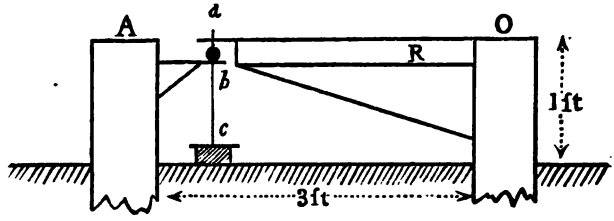
RELATIVE MOTION OF NEIGHBOURING POINTS OF GROUND.

By John Milne.

[Read January 26th, 1887.]

The following notes describe a series of experiments which were made to determine how far two or more points situated within three or four feet of each other synchronized in their movements when disturbed by an earthquake. The importance of such an investigation will be recognized when we reflect upon the relative effects which would be produced upon a rigidly constructed building under the two following circumstances, first when the ground to which the building was attached moved as a whole, and second when a portion of the ground upon which the building stood was moving in one direction while another portion moved in another direction. In one case the building would simply suffer in consequence of the inertia of its various parts, while in the other these effects might be supplemented by a racking action at its foundation,—one portion receiving impulses in one direction while another portion received impulses in another. Again, if it was found that two points of ground situated within two or three feet of each other did not synchronize in their movement,

it would necessitate our placing two portions of any seismograph designed to record the motion of a point, upon the same pedstal or post. The manner in which the investigations were made will be understood from the accompanying sketch illustrating the apparatus which was employed.



A heavy post about 9 in. in diameter was driven to a depth of about 2 ft. in the ground, 1 ft. projecting above the surface. On the South, North-west, and North-east sides of this, three similar posts, *A*, *B*, and, *C* were also driven in the ground. In the sketch only one of these is shown. Radiating from *O* in the direction of *A B* and *C* were three light arms, one of which *Oa* is shown in the sketch. These were made of light deal, and to give them rigidity they were stiffened by a broad horizontal rib marked *R*, so that the arm had a + section. At *a* there was a conical hole in a brass plate which was immediately above a similar hole in a light brass bracket firmly fixed to the post *A*. If the motion of the post *O* coincided with that of the post *A*, then these holes it was assumed would remain above each other. To test whether this was the case a light multiplying lever *a b c* was passed through these holes, terminating with a sliding needle pointer at *c* which rested on a smoked glass plate. Any relative motion of *a* and *b* would be shown by a multiplied representation (6 times) of such movement on the plate. At *B* and *C* there were similar arrangements. The only source of error would be a switching movement of the arm *Oa*. This, however, I do not think likely. The results of the observations which show that in all earth-

quakes there was a motion of *O* relative to *A*, *B* and *C* are given in the following notes and table:—

RELATIVE MOTION.

November 21st, 1884.

Plate S. .....4 mm. S.W.
Plate N.W. .....2·2 mm. in several directions.
Plate N.E. .....No visible mark, probably rubbed off.

November 24th, 1884.

Plate S. .....1 to 0·8 mm. mostly S. to W.
Plate N.W. .....2 mm. or 0·5 mm.—2 mm. is probably not the earthquake motion.
Plate N.E. .....mere dot.

November 27th, 1884.

Plate S. .....1·3 mm. in several directions.
Plate N.W. .....1·4 mm. mostly N.W. marked "Partly made when taking out."
Plate N.E. .....No mark.

November 29th, 1884.

Plate S. .....0·9 mm. ?, apparently 0·5 mm.
Plate N.W. .....0·5 mm.
Plate N.E. .....0·4 mm.

December 1st, 1884.

Plate S. .....Motion of 5 to 6 mm. in S.W. This might have been produced by the pointer swinging or creeping out, as seen from the diagram.
Plate N.W. .....2.2 mm. W.N.W.
Plate N.E. .....Mere dot.

December 6th, 1884.

Plate S. .....1 mm.
Plate N.W. .....1 or 2 mm.
Plate N.E. .....——?

December 7th.

N.W. 1 or 2..... S. a dot..... N.E. dot.

December 9th.

N.W. 1 or 2. ..... S. a dot. ..... N.E. dot.

December 14th.

N.W. 1 or 2. ..... S. irregular 5 mm. ? ..... N.E. dot.

December 16th.

N.W. 2. ..... S. a dot. ..... N.E. dot.

January 24th.

N.W. 1 mm. ..... S. 3 or 4 mm. ..... N.E. 5 mm.

February 1st.

N.W. 1 mm. ..... S. a dot. ... N.E. irregular motion.

February 4th.

N.W. 1 or 2 mm. ..... S. a dot. ..... N.E. 4 mm.

February 6th.

N.W. a dot..... S. a dot. ..... N.E. a dot.

MOTION OF THREE POINTS RELATIVELY TO A FOURTH.

No.	DATE.	INTENSITY.	SOUTH.	NORTH-WEST.	NORTH-EAST.
	1884				
—	Nov. 21	—	4.	2.2	—
—	Nov. 24	—	1.	2.	—
—	Nov. 27	—	1.3	1.4	—
—	Nov. 29	—	.9	.5	.4
—	Dec. 1	—	566?	2.2	—
—	Dec. 6	—	1.	1.5	—
—	Dec. 7	—	—	1.5	—
—	Dec. 9	—	—	1.5	—
—	Dec. 14	—	.5	1.5	—
—	Dec. 16	—	—	2.	—
	1885				
—	Jan. 24	—	3.5	1.	5.
—	Feb. 1	—	—	1.	—
—	Feb. 4	—	—	1.5	4.
—	Feb. 6	—	—	—	—

THE MOVEMENT PRODUCED IN CERTAIN BUILDINGS BY EARTHQUAKES.

By John Milne.

[Read January 26th, 1887.]

The following experiments were made with the object of measuring the relative amounts of motion felt at the time of an earthquake in buildings of different construction and in different parts of the same building. The buildings chosen are situated upon the grounds of the Imperial College of Engineering in Tokyo, one of them being inhabited by myself and the other, which is situated on similar ground about 60 feet distant, by Professor Alexander. The relative position of these buildings is shown in a plan of the Imperial College of Engineering published in connection with a paper on a seismic survey in Vol. X. of the Society's publications. My house, which has an upper story and is built of brick with a heavy tile roof and an internal wooden framing, forms the western end of a row of three houses running from S. 35° E. to N. 35° W.

As it is the last house in a row the direction of which approximately coincides with a direction of considerable motion, its position is not a good one. This assumption is born out by the fact that it has recently been cracked from top to bottom and some of the stone work at the angles pushed forward. Professor Alexander's house, which has recently been pulled down, was built of wood, and covered externally with plaster. The roof, like mine, was tiled. Both houses had an upper story.

In each of these houses pendulum seismographs were placed, one upstairs and one downstairs, vertically above each other and as nearly as possible in similar positions. They stood upon the wooden floors, which measured vertically

were approximately 13 feet apart. The doors of the instruments (which are described on p. 91 of Vol. IV. of the Society's Transactions) in my house faced N. 60 E., and in Professor Alexander's house N. 30 W.

In looking at the following records, which were very kindly drawn up by Professor Sekiya and subsequently revised by myself, it must be remembered that the actual movement experienced is only one-eighth of that which is recorded. Several of the records obtained at Professor Alexander's house, especially those which were recorded for down stairs, are untrustworthy owing to the instrument having been in the vicinity of the front door and therefore subject to accidental disturbance. There is, however, little difficulty in distinguishing between the records obtained from an earthquake and those due to an accidental swinging of the pendulum.

Here and there a few records as given from an earthquake house resting on balls have been interpolated. Here a long, slow, surging motion was produced, and although the amplitude of motion was great its severity was mitigated by the increase in period. Subsequently the house was placed on layers of cast iron shot, and the aseismic character of the foundations greatly improved. (See Seismic Experiments. Trans. Seis. Soc., Vol. X.)

The earthquake house records were taken on the solid ground between my house and that of Professor Alexander.

January 2nd, 1884.

Milne's House upstairs.—1.6 mm. N. 15° E. There is a record of larger motion, but that is not perhaps the earthquake motion.

Earthquake House.—2 mm. W.E.

January 10th, 1884, 9 p.m.

Milne's House upstairs.—4.2 mm. N. 50° E. There is one stroke of 5.5 mm. which is perhaps an earthquake motion.

Milne's House downstairs.—3.5 mm. N. 70° E.

Earthquake House.—Very complicated diagram: 4.5 mm. in form of a circle.

January 19th, 1884, 12.55 p.m.

Milne's House upstairs.—3 mm. (?) very complicated diagram which is difficult to measure. Direction mostly N.E.

Milne's House downstairs.—2 mm. N. 20° E. (marked on the plate "evidently too small").

Earthquake House.—7 to 9 mm. mostly N.E.; very complicated diagram.

February 10th, 1884.

Milne's House upstairs.—2 mm.

February 22nd 1884, 5 a.m.

Earthquake House on Ground.—0·8 mm., the direction variable.

Milne's House upstairs.—1.1 mm., N. 45 E. very distinct.

Earthquake House on Balls.—Mostly 1.5 mm., the direction variable; there are also waves of 4 mm. although they might not have been produced by earthquake.

February 22nd 1884, 6 p.m.

Alexander's House upstairs.—7 mm. (maximum) in the direction of the door, but there were motions (5 to 4 mm.) in several directions—motion of rotation. The record is good.

Alexander's House downstairs.—Very indistinct, perhaps 2.5 mm. Record fairly good.

Milne's House downstairs.—1.1 mm. Direction uncertain.

February 10th, 1884.

Milne's House upstairs.—1.5 mm. N. 60 W.

March 3rd, 1884.

Milne's House upstairs.—2 mm. N. 30° E. distinct.

Milne's House downstairs.—0.5 mm.

Earthquake House.—1 mm. indistinct.

Alexander's House upstairs.—9 mm. (maximum) 30° left, and other motions 6.3 mm. of much variety. Good record.

Alexander's House downstairs.—Very indistinct. Say 5 mm.

Aseismic House.—19 mm. in the direction of the door and motion of 12 mm. in other directions. Probably the instrument (or house) moved with its own period of vibration.

March 7th, 1884.

Milne's House upstairs.—2.2 mm. N. 45° W. The pointer had been creeping.

Milne's House downstairs.—1.1 mm. N. 60° W.

Earthquake House.—1.3 mm. N. 25° E. Indistinct.

Alexander's House downstairs.—6 mm. N. 25° E.; marked on the plate "very doubtful."

Alexander's House upstairs.—4 mm. N. 25 E.; marked on the plate "very doubtful."

March 7th, 1884, 1.15 p.m.

Aseismic House.—6 mm. N. 20 W.; marked on the plate "this is doubtful." Complicated diagram.

March 13th, 1884, p.m.

Alexander's House downstairs.—(3) mm. ? direction N. 30° W.

Alexander's House upstairs.—7 mm. N. 20° W. motion of long duration.

March 14th 1884, a.m.

Milne's House upstairs.—1 mm. N. 35° E.

Milne's House downstairs.—The diagram incomplete; it is difficult to judge how far the house moved; perhaps much friction in the instrument.

Earthquake House.—0·9 mm. in variable direction.

Alexander's House downstairs.—15 mm., motion of very long duration. Probably the instrument moved.

March 14th, 1884, 9 p.m.

Milne's House upstairs.—0.8 mm.; small dot.

Milne's House downstairs.—1.5 mm. in single stroke, but very incomplete diagram; too much friction or instrument moved.

Earthquake House.—1 mm. in a few strokes.

Alexander's House upstairs.—Described a circle whose diametre is 1.8 mm.

Alexander's House downstairs.—2 mm. in the direction of the door. Rather difficult to measure.

NOTE.—This earthquake was undoubtedly a short one as seen from all diagrams.

Aseimic House.—17 mm.; complicated motion of long duration; instrument moved by some outside disturbance.

March 15th, 1884, 8.24.0 p.m.

Milne's House downstairs.—2 mm. N. 20° E. in one stroke, but rather doubtful whether this is an earthquake motion.

Milne's House upstairs.—1.7 mm. N. 60° E. in a few strokes.

Earthquake House.—2 mm. in several directions.

Alexander's House downstairs.—3 mm. N. 30° E.

Alexander's House upstairs.—10 mm. N. 60° E. elliptical figures of various magnitudes in the same direction; good diagram.

Aseismic House.—20 mm. 70° right. Very complicated figure, and motion of very long duration. Apparently the house and instrument moved considerably.

Aseismic House.—17 mm. 45° Right. The same remarks apply in this figure as stated for the above diagram.

March 17th, 1884, 9.30.0 p.m.

Milne's House (?)—1.5 mm. N. 25 E.

Upstairs (?)—2 mm. in the direction of the door in a few strokes.

Earthquake House.—1.5 mm. in several directions.

Alexander's House downstairs.—3 mm. mostly N.E., not very clear; good record.

Alexander's House upstairs.—6 or 7 mm., mostly N.E. also large motion in other directions; good record.

March 26th, 1884, 12.50 p.m.

Milne's House upstairs.—5 mm. N.E. direction very distinct.

Milne's House downstairs.—2.5 mm. N.S.

Earthquake House.—3 or 4 mm. in several directions. Pointers had been creeping.

Alexander's House upstairs.—10 mm. N.E. and large motion in other directions; good record.

Alexander's House downstairs.—5 mm. N. 25° E.

April 6th, 1884.

Milne's House downstairs.—2 mm. to 3.5 mm. in various directions.

Milne's House upstairs.—4 mm. N.E.

Earthquake House.—5 mm. S. 25° W.

Alexander's House upstairs.—9 mm. in several directions.

Alexander's House downstairs.—Very indistinct, probably 2.5 mm. (Rather too small for Alexander's House, apparently the instrument was *not* in good order.)

May 6th, 1884.

Milne's House upstairs.—4.5 mm. N. 32° E.

Milne's House downstairs.—3 mm. 25° left.

Earthquake House.—6 mm.—8 mm. in several directions.

Alexander's House upstairs.—4.5 mm. N. 45° W.; doubtful record.

Alexander's House downstairs.—18 mm. N. 10° W.; doubtful record.

May 11th, 1884, 8 p.m.

Milne's House upstairs.—5.5 mm. N. 40° E.

Milne's House downstairs.—3 mm. in several directions.

Earthquake House.—2.2 mm. in various directions.

Alexander's House upstairs.—7 mm. N. 50° W.

Alexander's House downstairs.—5 mm. in several directions.

May 12th, 1884:

Milne's House upstairs.—1 or 2 mm.

Milne's House downstairs.—1 or 2 mm.

May 19th, 1884.

Milne's House upstairs.—2.2 N. 25° E.

Milne's House downstairs.—2.2 mm. in several directions.

Earthquake House.—1.8 in various directions.

Alexander's House upstairs.—1.7 N. 60° W.

Alexander's House upstairs.—Large but indistinct diagram. About 3 mm.

May 20th.

Milne's House upstairs.—2.8 mm. N.

Milne's House downstairs.—0.5 mm.; a small mark.

May 23rd.

Milne's House upstairs.—1.1 mm. ?
Milne's House downstairs.—1 mm. ?
Earthquake House.—1.8 or 2.5 mm.
Alexander's House upstairs.—2.2 mm. N.W.
Alexander's House downstairs.—3 mm. NW.

May 27th, 1884.

Milne's House upstairs.—2·5 mm. ?, very indistinct.
Milne's House downstairs.—2 mm.
Earthquake House.—2 mm. N. 25° E.
Alexander's House upstairs.—7 mm. Mostly N.W., good record.
Alexander's House downstairs.—Diagram of large motion, but difficult to give measurement, and record not good.

May 30th, 1884.

Milne's House upstairs.—5 mm. N.E.
Milne's House downstairs.—2.5 mm.
Earthquake House.—1.5 mm. N.E.
Alexander's House upstairs.—4 mm. W. N.W., good record.
Alexander's House downstairs.—6 mm. W. N.W., not good. Evidently due to accidental shaking.

May 31st, 1884.

Milne's House upstairs.—1.5 mm. N.
Milne's House downstairs.—1.5 mm. 30° Right.
Earthquake House.—2 mm.

June 8th, 1884.

Milne's House upstairs.—2.5 mm. ? N. 32° E.
Milne's House downstairs.—1—1.8 mm. N.
Earthquake House.—2 mm.

June 11th, 1884.

Milne's House upstairs.—3.5 mm.
Milne's House downstairs.—Creeping and indistinct diagram.
Earthquake House.—2.8 mm.

December 22nd, 1883, 6.45 a.m.

Milne's House upstairs.—5 mm. chiefly E.W.

Earthquake House.—3.5 mm. N.E. to S.W.

November 30th, 1883, 4 a.m.

Milne's House upstairs.—5 mm. N.E. to S.W.

Milne's House downstairs.—1 or 2 mm.

The above observations have been tabulated as follows :—

MOTION RECORDED IN DIFFERENT PARTS OF DIFFERENT BUILDINGS.

NUMBER.	DATE.	BRICK UPSTAIRS.	BRICK DOWNSTAIRS.	WOOD UPSTAIRS.	WOOD DOWNSTAIRS.	OUTSIDE ON GROUND.	ASEISMIC HOUSE ON BALLS.
	1883.						
	Nov. 30	5	1.5	—	—	—	—
	Dec. 22	5	3.5	—	—	—	—
	1884.						
	Jan. 2	1.6	—	—	—	2	—
	Jan. 10	4.2	3.5	—	—	4.5	—
	Jan. 19	3	2	—	—	7	—
	Feb. 10	2	—	—	—	—	—
	Feb. 10	1.5	—	—	—	—	—
	Feb. 22	1.1	—	—	—	.8	1.5
	Feb. 22	—	1.1	7	2.5	—	—
	Mar. 3	2	.5	9	5	1	—
	Mar. 7	2.2	1.1	?	—	1.3	6
	Mar. 14	.8	1.5	1.8	2	1	17 & 19
	Mar. 15	1.7	?	10	3	2	20 & 17
	Mar. 17	2	—	7	3	1.5	—
	Mar. 26	5	2.5	10	5	3	—
	April 6	4	2	9	2.5	5	—
	May 6	4.5	3	?	?	6	—
	May 11	5.5	3	7	5	2.2	—
	May 12	1	1	—	—	—	—
	May 19	2.2	2.2	3	—	1.8	—
	May 20	2.8	.5	—	—	—	—
	May 23	1.1	1	2.2	3	1.8	—
	May 27	2.5	2	7	—	2	—
	May 30	5	2.5	4	—	1.5	—
	May 31	1.5	1.5	—	—	2	—
	June 8	2.5	1.8	—	—	2	—
	June 11	3.5	—	—	—	2.8	—
General Average.	—	2.8	1.8	6.1	3.5	2.5	11.1

CONCLUSION.

In the last line of the preceding table a general average is given for the amount of motion felt in different houses and in different parts of the same house, from which it appears that the least motion is felt downstairs in the brick house, more

upstairs, rather more downstairs in the wooden house, and the greatest motion upstairs in the wooden house.

Calling the motion experienced downstairs in the brick house 1, then the motion respectively experienced upstairs in the same house and downstairs and upstairs in the wooden house becomes 1.6, 2, and 3.4. Why the motion outside, that is in the earthquake house, should be greater than that felt downstairs in the brick house, it is difficult to explain. Perhaps it may be due to the relative position of the two places, or perhaps to the fact that the brick house has tolerably deep foundations (see Seismic Survey. Trans. Seis. Soc., Vol. X.).

The large motion in the aseismic building has already been explained. With the new foundations this no longer exists.

It will be observed that a fairer method of obtaining an average would have been only to consider those earthquakes which were recorded upstairs and downstairs in both buildings; such a set of averages have, however, been found to be practically the same as the general average.

EARTHQUAKES IN COREA.

By W. G. Aston.

[Read January 26th, 1888.]

In Dr. J. Macgowan's paper on earthquakes in China, read before this Society last year, he speaks of the absence from the Corean annals of all reference to earthquakes in that country, from which he concludes that Corea is comparatively exempt from seismic action. He quotes a letter from the Prefect of Chemulpo to Mr. E. H. Parker to the effect that earthquakes are so infrequent and harmless that records are not kept of their occurrence.

The following list of earthquakes in Corea prepared from the standard histories of that country, the Tongkuk thong-kam and the Kuk-cho pong-kam, shows that Dr. Macgowan's statement is not strictly correct, but it lends at the same time strong confirmation to his inference that Corea is comparatively exempt from seismic action. Counting as one those which took place within a few days of each other, only 27 earthquakes have been recorded during a period of over 1,800 years (B.C. 57 to A.D. 1766) which is covered by the histories just mentioned. Even this number is perhaps too large, for where thunder is mentioned at the same time, it is possible that nothing more than the quaking of the earth from this cause may have been intended. Of the whole number, only two seem to have been at all severe. In A.D. 719, houses were destroyed, and 100 persons lost their lives, and in 1518, an earthquake occurred which is described as severe, and lasting four days.

Taking the 10th, 11th, 12th, 1st, 2nd, and 3rd as the cold, and the others as the warm months, fourteen earthquakes

occurred in the former and thirteen in the latter, but of course these numbers are too small to have any scientific value.

During the earlier part of Corean history, earthquakes are recorded in each of the three kingdoms, Silla, Kokuli, and Pèkché, into which that country was then divided. After the union of the country into one kingdom under the name of Chōsen, we may assume that the earthquakes recorded took place at or near the present capital.

Ten of the whole number recorded belong to the period of forty-seven years from A.D. 1338 to 1384 inclusive, which seems therefore to have been a time of unusual seismic activity —*i.e.* if anything like a careful record has been kept.

List of Earthquakes in Corea.

Date.	Place.	Remarks.
A.D. Chinese month & day.		
142... 9	Kokuli (Jap. Kōrai)	
299...11	Do.	Thunder at the same time.
616...11	Chŏlla-do	
637... 2	Do.	
637... 3	Do.	
681... 5	Silla (Kangwŏn-do)	
717... 3	Do.	
717... 4	Do.	
719... 3	Do.	Houses destroyed, 100 persons killed.
972... 2	Kokuli	
1134... 5...29	Kwang-ju (near Sŏul)	Accompanied by a bloody rain.
1134... 6... 1	Kokuli	
1153... 3... 7		
1159...11...15	Do.	Morning.
1338... 6... 3	Do.	Two shocks, the latter at night.
1338... 6...12		
1338... 6...19		
1338... 6...23		
1338... 6...24		
1338... 8...20		
1339... 5... 3	Do.	
1339... 9...11	Do.	
1343... 3	Do.	On two days in the month.
1345... 1...30	Do.	
1362...11...13	Do.	
1366...10... 5	Do.	Great thunder.
1366...10... 8	Do.	
1374...11... 8	Do.	Great rain and thunder.
1384... 5...10	Do.	
1518... 5	Do.	Lasted for four days—not at the capital.—A severe earthquake.
1556... 5	Do.	Rain, hail, and earthquake.
1643... 5	Do.	
1681... 5	Do.	

EARTHQUAKE SAFETY LAMPS.

By S. Sekiya.

[Exhibited January 26th, 1888.]

In the Transactions of this Society, Vol. XI., p. 88, I pointed out that the use of some sort of safety lamp would act as a safe-guard against accidents not only at the time of severe shocks, but also in our daily life, and I particularly mentioned the "Shaftesbury" safety lamp patented in England. A sample of this lamp lately arrived in this country. It is represented in Fig. 1 and Fig. 2. The mechanism is such that, when the lamp is either inclined on one side or dropped, the flame is automatically and instantly extinguished. The arrangements consist of a sliding rod *r r* passing through the body of the lamp, and having the upper end hinged to an extinguishing cap *c*, while to the lower end a small weight is attached. When the weight rests on a table the cap is removed from the wick as shown in the figure, but when the lamp is tilted a little out of the perpendicular the weight pulls the cap down over the wick and extinguishes the flame. In order to prevent the lamp from being extinguished when lifted off the table a sliding ring is attached to its stem so that the hand in grasping it locks the mechanism. By this means the lamp can be moved without putting out the light, but should the lamp fall from the hand the cap goes up instantly before it can reach the ground. The price of the lamp is two shillings and nine pence (nearly 90 *sen*) and upwards; its patentee is Mr. Edward Phillips, No. 1, Holburn Viaduct, London.

Lamps of like nature have been patented in this country, but they are mostly poorly made. An exception is the one shown in Fig. 3, which, though not so ingenious and certain as its English rival, is fairly effective and exceedingly cheap.

A mouth-piece or gallery containing the whole of the extinguishing mechanism can be bought at the very low price of 10 sen (four pence) and upwards, and it can be fitted to lamps of certain fixed size. In this the mechanism consists of two flaps hinged to, and radiating from, the root of the wick pipe. A thick wire forming a lever passes horizontally into the gallery; to one end of this wire two short wires are attached, each being hinged into the flap. To the other end a spiral spring is fixed so as to shut the flaps by means of the thick wire lever. A counter weight is hung on one side of the lever and keeps the flaps open, but whenever the lamp is hit or knocked over either the spring slackens its force or the weight entirely falls down from its hold; this shuts the flaps instantly extinguishing the flame. I have both used and tested this lamp. It answers the purpose fairly well. The patentee is Mr. K. Yoshikawa, Tawarachō, Asakusa, Tokyō.

After the above description of safety lamps, it may not be out of place to briefly mention the accidents which have occurred from petroleum lamps. In the great earthquake of Yedo in 1855, fire broke out at no less than thirty-seven points. This was at a time when petroleum was unknown in this country, and now almost every one of the 200,000 houses in this city use one or more petroleum lamps; shops generally use a large number. The danger with which we are threatened by oil lamps at the time of another destructive shock is therefore not difficult to imagine. The danger which occurs daily is, however, more serious in the long run than that caused by earthquakes. Tōkyō Fire Reports from 1886 to 1887 give 953 outbreaks of fire, out of which 118 cases, or more than 12 per cent., were caused from petroleum oil. This is not to be wondered at when we consider the flimsy lamps now in such extensive use and the brittle materials of which they are made.

Considering these few facts, it would seem that the inhabitants of large cities, where the dangers from earthquakes and fires are abnormally great, as in this country, could not fail but derive great benefit by using either safety lamps, or at least lamps with metallic oil vessels.

Fig. 1.

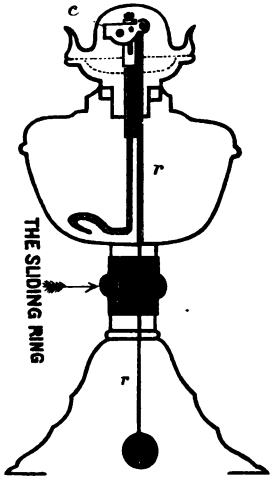
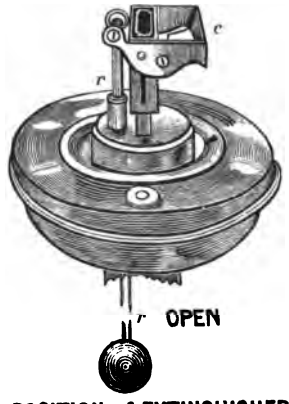


Fig. 2.



POSITION of EXTINGUISHER WHEN ALIGHT.

Fig. 3.

EARTHQUAKE MEASUREMENTS OF RECENT YEARS ESPECIALLY RELATING TO VERTICAL MOTION.

By S. Sekiya.

[Read February 23rd, 1888.]

This paper contains the records of earthquake observations made during the two years from September, 1885, to September, 1887. Severe shocks as well as feeble tremors are arranged in the accompanying table, and in some shocks separate notes are added by way of fuller description. The measurements were made at two places in Tōkyō; one set at Hitotsubashi, where the ground is soft and marshy, and the other set at Hongō, where the soil is hardened alluvial mud.

Vertical motion, which forms the principal subject in this paper, has not hitherto been so much studied as horizontal motion. This is on account of its comparatively rare occurrence, and when it occurs its smallness makes it of secondary importance to the more prominent horizontal movement. Reference will be made to Plates IX., XI., and XXVI., Vol. I. of the Journal of the Science College, Imperial University, Japan, and Transactions of this Society Vol. XI., p. 176, Plate I., in which the characteristic features of vertical motion occurring in conjunction with horizontal motion can be seen.

In this country absolute vertical motion[1] was first measured by Mr. E. Knipping between 1878 and 1880. During that period eight observations were made; in four cases the vertical motion reached 0.02 mm. The largest value, 0.56 mm., was

[1] Mittheilungen der Deutschen Gesellschaft, etc. Ostasiens Vol. 17, May, 1879, and Transactions of the Seismological Society of Japan, Vol. I. p. 72.

observed in the severe earthquake of February 22nd, 1880. In 1883, Professor J. Milne, in conjunction with Professor T. Gray, made experiments on artificial earthquakes.[2] Vibrations then were caused by letting fall a heavy weight from various heights or exploding dynamite in holes made in the ground. His results were principally as follows:—(1) In the soft ground vertical motion appears to be a free surface wave which outraces the horizontal components of motion. (2) Vertical motion commences with small rapid vibrations and ends with vibrations which are long and slow. (3) High velocities of transit of seismic waves may be obtained by the observation of this component of motion. It is possibly an explanation of the preliminary tremors of an earthquake and the sound phenomena.

In the table are given the following quantities:—

1. Maximum Motion ($2r$) or the largest range of the displacement of the ground in each shock.

2. Complete Period (t) of the maximum motion or the time taken to make a complete to-and-fro motion of the ground.

3. Maximum Velocity (v) of the ground, or $v=\frac{2r\pi}{t}$.

4. Maximum Acceleration $=\frac{v^2}{r}$.

The last two quantities were calculated by assuming for convenience sake the motion of the ground to be harmonic, though it is not exactly so in actual cases.

5. Direction of the maximum horizontal motion of the ground.

6. Duration of the earthquake, *i.e.*, the interval of time from the commencement to the end of the disturbance. It is almost impossible to measure the absolute duration of earthquakes, as they usually begin with exceedingly feeble tremors and end with very slow undulations.

7. The distance and direction of the origin of each earthquake from Tōkyō and its area. These were kindly supplied

[2] Transactions of the Seismological Society, Vol. VIII.

by the Imperial Meteorological Observatory. Existence of vertical motion, the range and the direction of horizontal motion, etc., may be examined in reference to the position of the origin of shocks and their area.

By *Tremors* are meant feeble shocks whose range of motion is less than one-tenth of a millimeter.

Local shocks, marked *Local*, are small earthquakes, shaking only limited regions of the country, usually from five to fifteen miles around.

Professor J. A. Ewing's Horizontal Pendulum and Vertical-motion Seismographs were mainly used in making these measurements. They are automatically started by the earthquake motion when it attains one-fifteenth part of a millimeter. By increasing the sensitiveness of the instruments the number of records may be proportionally increased.

The records, unless otherwise stated, are those obtained at Hitotsubashi.

1885.

No.	Date.	Max. Horiz. Motion in mm.	Complete Period of Max. Horiz. Motion in Sec.	Max. Velocity in mm. per Sec.	Accel. in mm. per Sec. per Sec.	Direction of Max. Horiz. Motion.	Duration of Horiz. Motion.	Max. Vertical Motion in mm.	Complete Period of Vertical Motion in Sec.	Duration of Vertical Motion.	Distance and direction of origin from the observatory in miles.	Radius of propagation of seismic waves in miles, or area of disturbance in sq. miles.
							min.sec.			min.scc.		
1	Sept. 2, 8.36. 0. p.m.	0.3	0.8	1.2	9.6	NNE	2.30	0.05	0.70	0.46	46 miles due North inland.	54 m.
2	Sept. 26, 0.30. 0. p.m.	6.5	2.2	9.3	26.6	N76°W	3.35	0.14	0.56	1.42	110 miles S 30 W in the ocean.	146 m.
3	Sept. 28, 5.28. 0. a.m.	3.8	1.7	7	25.8	EW	3.00	Trace			The same in general features as No. 2.	
4	Sept. 29, 8.36.16. a.m.	0.1	1	0.3	2.	SN	1.45				Local.	
5	Oct. 1, 1. 9. 0. p.m.	1	0.7	4.5	40.5	SN	2.00	0.10	0.40	0.09	59 miles N 35 E on the sea shore.	90 m.
6	Oct. 3.	0.1	1	0.3	2.	SN	0.50				Local.	
7	Oct. 7, 7.34.45. a.m.	0.4	0.7	1.8	16.2	N15°E	0.18				Local.	
8	Oct. 9, 7.54. 0. p.m.	0.1	0.8	0.4	3.2	EW	2.00				Local.	
9	Oct. 11, 5.28.18. a.m.	1.1	1	3.5	22.3	WNW	4.03	0.02		0.06	71 Miles N 60 E in the sea.	83 m.
10	Oct. 15, 9. 2.29. a.m.	0.3	0.8	1.2	9.6	W15°N	1.10				178 miles WSW.	14,333 sq. m.
11	Oct. 15, 8.18.43. p.m.	1.0	0.7	4.5	40.5	ESE	2.28	0.03		0.07	15 miles SSE in Tokyo Bay.	33 m.

12	Oct. 18, a.m.	Tremors				EW	0.20				Local.	
13	Oct. 18, 0.15. 0. p.m.	0.3	0.9	1.6	17.1	NS	1.00				N60°E 59 miles.	61 m.
14	Oct. 21, 1.15. 0. a.m.	0.4	0.9	1.4	9.8	NW	2.02				98 miles N 73° W	19,500 sq. m.
15	Oct. 24, 5.12.18. p.m.	0.7	0.9	2.4	16.0	S60°W	1.15				81 miles nearly E in the sea.	93 m.
16	Oct. 26, 10.41.11. p.m.	2.2	1.4	4.9	21.8	EW	3.20				112 miles S in the sea.	139 m.
17	Oct. 30, 8.31.16. p.m.	0.3	1.0	0.9	5.4	WNW	2.30	Trace			415 miles NW in the ocean.	34,700 sq. m.
18	Nov. 16, 1.53.36. p.m.	Tremors					0.30				15 miles SSE.	22 m.
19	Nov. 18.	Tremors				NS					Local.	
20	Dec. 3, 6. 1.42. a.m.	0.2	0.6	1.0	10.	NS	1.00				20 miles NNE inland.	29 m.
21	Dec. 7, 1. 2. 0. a.m.	2.1	1.6	4.1	16.0	NNW	5.02				98 miles E 13° N in the sea.	17,120 sq. m.
22	Dec. 19, 2.12. 0. a.m.	Tremors				NS	0.43				Local.	
23	Dec. 19, 6.28. 0. p.m.	2.8	1.7	5.2	19.4	S55°W and then to N 30° W	1.46	0.22	0.50	0.45	37 miles E 35° N inland.	160 m.
24	Dec. 25, 1.13.30. p.m.	0.2	0.7	0.9	8.1	EW		Trace		0.10	Local.	
25	Dec. 28, 10. 6.30. p.m.	3.5	1.4	7.9	35.7	EW	3.30	1.00	0.60	1.62	29 miles NNE inland.	98 m.

1886.

No.	Date.	Max. Horiz. Motion in mm.	Complete Period of Max. Horiz. Motion in Sec.	Max. Velocity, in mm. per Sec.	Accel. in mm. per Sec. per Sec.	Direction of Max. Horiz. Motion.	Duration of Horiz. Motion.	Max. Vertical Motion in mm.	Complete Period of Vertical Motion in Sec.	Duration of Vertical Motion.	Distance and direction of origin from the observatory in miles.	Radius of propagation of seismic waves in miles, or area of disturbance in sq. miles.
							min.sec.			min.sec.		
26	Jan. 4, 8.31.30. p.m.	0.4	0.7	1.8	16.2	EW	0.54				59 miles N 60° E in the sea.	61 m.
27	Jan. 5, 4.26.42. p.m.	0.8	1 ·	2.5	15.8	EW	0.75	Trace			66 miles due E on the sea shore.	73 m.
28	Jan. 9, 6.48.0. a.m.	0.1	1.2	0.3	1.8	SN	2.00				Local	
29	Jan. 18, 9.15.0 p.m.	0.3	0.8	1.2	9.6	NS	0.65				Local	
30	Feb. 18, 3.0.0. a.m.	0.2	0.7	0.9	8.1	EW	0.22				Local	
31	Feb. 19, 9.51.11. a.m.	0.1	1	0.3	1.8	EW	0.15				Local	
32	Feb. 22.	0.1	0.7	0.4	3.2	EW	0.40				Local	
33	Feb. 24, 7.34.0. a.m.	0.5	0.6	2.6	27.0	NW	1.45	0.08	0.3	0.56	29 miles due N inland.	73 m.
34	Feb. 24, 3.36.25. p.m.	0.3	1	0.9	5.0	EW	1.20				Local	
35	March 2, 5.3.49. a.m.	0.6	0.8	2.4	19.2	NNE	2.10				73 miles due E in the sea shore.	78 m.

36	March 3, 3.36.0. p.m.	Tremors				EW	0.15				Local	
37	March 13, 6.25.0. p.m.	0.7	0.9	2.4	16.2	WNW	2.00				68 miles nearly E on the sea shore.	73 m.
38	March 26, 6.6.0. p.m.	0.1	0.8	0.4	3.2	SSE	0.65				17 miles SSE in the bay.	24 m.
39	April 1.	0.1	1	0.3	1.8	EW	0.65	Trace		0.04	Local	
40	April 4, 1.0.0. a.m.	0.4	1	1.3	8.0	EW	2.10	Trace		0.15	134 miles NNE away in the sea.	146 m.
41	April 13, 4.45.0. a.m.	1.2	0.9	4.2	29.2	S54E	4.02	0.05	0.4	0.10	342 miles SE in the ocean.	33,000 sq. m.
42	April 14, a.m.	0.8	0.9	2.8	19.6	EW	0.40				Local	
43	April 23, 4.22.22. a.m.	0.7	0.8	2.7	20.8	ENE	1.26				171 miles NW on the other side of the island.	16,400 sq. m.
44	May 2, p.m.	0.1	0.9	0.4	3.2	WE	0.40				Local	
45	May 3, 0.0.0. p.m.	0.2	0.7	0.9	8.1	ESE	2.00				Local	
46	May 5.	0.2	0.9	0.7	4.9	EW	0.54				29 miles NNE inland.	32 m.
47	May 8, 10.14.0. p.m.	2.1	0.8	8.2	64.0	N47°E	2.24	0.33	0.5	0.44	32 miles WNW inland.	85 m.
48	May 9, 3.0.0. p.m.	0.5	1.2	1.3	6.8	E30°N	2.50				Local	

1886.

No.	Date.	Max. Horiz. Motion in mm.	Complete Period of Max. Horiz. Motion in Sec.	Max. Velocity, in mm. per Sec.	Accel. in mm. per Sec per Sec.	Direction of Max. Horiz. Motion.	Duration of Horiz. Motion.	Max. Vertical Motion in mm.	Complete Period of Vertical Motion in Sec.	Duration of Vertical Motion.	Distance and direction of origin from the observatory in miles.	Radius of propagation of seismic waves in miles, or area of disturbance in sq. miles.
							min.sec			min.sec.		
49	May 11, 2.31.58. p.m.	0.5	0.9	1.7	11.6	E10°S	1.25				Local	
50	May 16, 9.7.16. a.m.	3.3	1.2	8.6	44.8	N50°W	3.05	0.4	0.8	1.25	56 miles nearly NW inland.	18,530 sq. m.
51	May 18, 8.12.51. p.m.	0.5	0.9	1.7	11.6	S50E	2.15	0.1	0.3	0.36	29 miles NNE inland.	85 m.
52	May 30, 8.38.18. p.m.	0.4	0.9	1.4	9.8	EW (mainly)	1.30				57 miles NNE inland.	57 m.
53	June 3, 3.6.37. p.m.	0.4	1.1	1.1	6.1	EW	1.31	Trace			NE 76 miles in sea shore.	76 m.
54	June 6, 6.0.0. p.m.	0.5	0.7	2.2	19.4	EW	1.06	Trace			25 miles.	
55	June 11, 1.45.44 a.m.	Hongo. 0.1	0.7	0.4	3.2	NW	1.02				ESE in Tokyo Bay 15 miles.	35 m.
		Hitotsu-bashi 0.4	0.6	2.1	22.1	EW	1.15					
56	June 12.	0.5	0.7	2.2	19.4	WE	1.15				Local	
57	June 13.	0.3	0.9	1.0	6.7	EW	0.36				Local	

58	June 14, 6.25.19. p.m.		0.6	0.8	2.4	19.2	ESW	1.10	0.1	0.5	0.30	In or near Tokyo.	35 m.
59	June 22.		0.3	0.8	1.2	9.6	EW	0.52				Local	
60	June 28.		0.2	0.8	0.8	6.4	EW	0.31				Local	
61	July 2, 0.33.6. p.m.	Hongo.	0.7	1.0	2.2	13.8	ESE WNW	1.27	0.3	1.3	1.30	NE in the Pacific ocean.	Extensive earthquake shaking the whole of North Japan, Tokyo on its edge.
		Hitotsu-bashi.	1.8	0.9	6.2	42.7	ESE WNW	2.24	0.3	0.8	1.22		
62	July 23, 0.57.0. a.m.		0.6	0.9	2.1	14.7	NS	1.24				NW 110 miles on shore line.	Extensive shock, Tokyo on its edge.
63	August 3, 2.11.40 a.m.	Tremors					EW	0.20				N 30 miles inland.	30 m.
64	August 9, 11.24.0. a.m.	Hongo.	0.5	0.9	1.7	11.6	NE SW	1.44				The same as No. 62 in general features.	
		Hitotsu-bashi.	0.5	0.8	2.0	16.0	NE	1.10					
65	August 29, 8.34.54 p.m.		0.6	0.8	2.4	19.2	ESE	1.10					
66	Sept. 6, 0.38.53. p.m.		0.2	0.7	0.9	8.1	EW	0.35				Local	
67	Sept. 12, 8.43.22. p.m.		0.8	1.2	2.1	11.0	S30°W	0.50	0.1	0.4	0.16	In or near Tokyo.	65 m.

1886.

No.	Date.		Max. Horiz. Motion in mm.	Complete Period of Max. Horiz. Motion in Sec.	Max. Velocity in mm. per Sec.	Accel. in mm. per Sec. per Sec.	Direction of Max. Horiz. Motion.	Duration of Horiz. Motion.	Max. Vertical Motion in mm.	Complete Period of Vertical Motion in Sec.	Duration of Vertical Motion.	Distance and direction of origin from the observatory in miles.	Radius of propagation of seismic waves in miles, or area of disturbance in sq. miles.
								min. sec.			min. sec.		
68	Sept. 15, 3.9.23 a.m.		0.2	1.1	0.6	3.6	S 30° W	1.13	Trace			Local	
69	Sept. 16, 1.2.57 p.m.		0.1	0.4	0.8	12.8	SW	0.50	Trace			NNW 40 miles inland. Tokyo on edge.	50 m.
70	Sept. 21, 8.17.0. p.m.	Hongo.	0.2	0.9	0.7	4.9	EW	0.53					
		Hitotsubashi.	0.4	0.8	1.6	12.8	NS	1.31					
71	Sept. 30.		0.8	0.8	3.1	24.0	SN	0.58				Local	
72	Oct. 4, 2.35.25. p.m.	Hongo.	0.2	0.6	1.0	10.0	SW	0.24	0.1	0.4	0.15	NNE 25 miles inland.	40 m.
		Hitotsubashi.	0.3	0.9	1.0	6.7	WNW	1.25	0.1	0.5	0.24		
73	Oct. 22, 3.49.14. a.m.		0.5	0.8	2.0	16.0	NS	1.05				ENE 34 miles inland.	70 m.

74	Oct. 25, 10.11.18. p.m.		0.4	1.2	1.1	6.1	SE	1.40	0.1	0.5	0.34	The same in general features as No. 72.	
75	Nov. 1, 5.13.5. a.m.	Hongō.	0.3	1.9	0.9	5.4	NS	1.15	Trace				
		Hitotsu-bashi.	0.5	0.8	2.0	16.0	NS	0.59	0.1	0.5	0.16		
76	Nov. 2, 8.21.46. p.m.		0.2	1.1	0.6	3.6	WNW	1.40	0.1	0.6	0.33	N30 miles inland. NE in the Pacific ocean.	35 m.
77	Dec. 4, 2. 0.39. p.m.	Hongō.	0.3	0.8	1.2	9.6	SW	1.50	0.1	0.3	1.12	NE 120 miles in the Pacific ocean.	140 m.
78	Dec. 6, 0.40. 0. p.m.	Tremors						0.29				Local.	
79	Dec. 8, 11.58.16. a.m.		0.3	0.9	1.0	6.7	SN	2.02				N 30 miles inland.	35 m.
80	Dec. 11, 10.16.25. p.m.		0.4	0.9	1.3	8.5	SN	1.16	Trace			SE 150 miles in ocean near the shore.	120 m.
81	Dec. 12. 10.11.55. p.m.	Lost.											
82	Dec. 21, 3. 7. 2. a.m.	Tremors											
83	Dec. 26, 5.48. 5. p.m.	Hongō.	0.3	0.5	1.9	24.1	S 50°W	0.37	0.1	0.4	0.26	In or very near Tokyo.	65 m.
		Hitotsu-bashi.	0.8	0.6	4.2	44.1	NNW	0.51	0.3	0.6	0.21		

1886-1887.

No.	Date.	Max. Horiz. Motion in mm.	Complete Period of Max. Horiz. Motion in Sec.	Max. Velocity in mm. per See.	Accel. in m.m. per Sec. per Sec.	Direction of Max. Horiz. Motion.	Duration of Horiz. Motion.	Max. Vertical Motion in mm.	Complete Period of Vertical Motion in Sec.	Duration of Vertical Motion.	Distance and direction of origin from the observatory in miles.	Radius of propagation of seismic waves in miles, or area of disturbance in sq. miles.
							min.see.			min. sec.		
84	Dec. 29, 11. 5.43. a.m.	0.5	0.6	2.6	27.0	SE	1.0	0.2	0.5	0.18	N 22 miles inland.	43 m.
85	Jan. 15, 6.52. 0. p.m. Hitotsu-bashi. Hongō.	7.3	2.0	11.5	36.2	SSW	6.24 (Principal motion 2 min.)	1.3	1.0	1.12	35 miles.	200 m.
		21	2.5	26	66	S65°W	6.35 (do.)	1.8	0.9	1.38		
86	Jan. 16, 10.16.19. p.m.	0.6	0.7	2.7	24.3	Variable	1.55				The same in general features as No. 85.	
87	Jan. 24, 10.40.50. p.m.	0.4	0.7	1.8	16.2	EW	2.06				Local.	
88	Jan. 28, 3.54. 8. p.m.	0.4	0.8	1.6	12.8	ENE	1.05				NW in the Pacific ocean.	Extended along the coasts of North-Japan.
89	Feb. 2, 2. 8.14. p.m.	0.8	0.9	2.8	22.1	S 30° W	1.58				178 miles WSW.	180 m.
90	March 2, 5.33.21. p.m.	Tremors									Origin inland.	Small earthquake.
91	March 20, 11.32.56. p.m.	Tremors									Local.	
92	March 23.	0.3	0.8	1.2	9.6	WE	0.45				Local.	

93	April 4, 8.46. 0. a.m.	Tremors									N58 miles inland, Tokyo on edge.	65 m.
94	April 9, 11.49.54. a.m.	Tremors									The same as No. 93.	
95	April 16, 3.35. 0. a.m.	Hongō.	0.2	0.7	0.9	8.1	variable	0.40	Trace			ENE 35 miles.	37 m.
		Hitotsu-bashi.	0.4	0.8	1.6	12.8	SW NE	1.52	0.1	0.8	0.28	
96	April 20, 2.35. 0. a.m.		0.3	1	0.9	5.4	EW	0.40				Local.
97	April 23, 6.30. 0. p.m.	Tremors										Local.
98	April 27, 9.30.38. p.m.		0.5	2.7	0.6	1.4	SN	2.20				SSE in Tokyo Bay, 17 miles.	33 m.
99	April 29, 11.12.10. a.m.		1.4	Lost					(occurred)				
100	May 2, 11.25.40. a.m.	Hongō.	0.4	0.6	2.1	22.1	NE	0.57	0.1	0.5	0.17	In or near Tokyo.	
101	May 4.		0.8	1	2.5	15.6	ENE	1.12				Local.	
102	May 5, 2.35.10. a.m.		0.1	0.9	0.3	1.8	EW	0.35				Local.	
103	May 6, 3.49.50. p.m.	Tremors										Local.	
104	May 7, 7.13.12. a.m.		0.2	0.7	0.9	8.1	NS	1.27				The same in general features as No. 88, but smaller in extent.	

1887.

No.	Date.		Max. Horiz. Motion in mm.	Complete Period of Max. Horiz. Motion in Sec.	Max. Velocity in mm. per Sec.	Accel. in mm. per Sec. per Sec.	Direction of Max. Horiz. Motion.	Duration of Horiz. Motion.	Max. Vertical Motion in mm.	Complete Period of Vertical Motion in Sec.	Duration of Vertical Motion.	Distance and direction of origin from the observatory in miles.	Radius of propagation of seismic waves in miles, or area of disturbance in sq. miles.
								min.sec.			min.sec.		
105	May 9, 0. 9.14. a.m.		0.8	0.7	3.6	31.9	S65°W	2.11				Local.	
106	May 17, 4.19.44. p.m.		0.2	0.3	2.1	44.1	NS	0.20				N30 miles inland, Tokyo on the edge of the disturbance.	40 m.
107	May 21, 9.46.20. p.m.	Hongō.	0.4	0.6	2.1	22.1	NS	0.35				N 20 miles.	50 m.
108	May 29, 0.50.52. a.m.	Hongō.	0.6	1.8	1.0	3.3	NS	4.02	0.2	1.1	2.22	NNE 100 miles on shore-line, Tokyo in the middle of disturbed area.	Extensive shock.
		Hitotsu-bashi.	2.1	1.1	6.0	34.3	W10°N	4.30	Lost				
109	June 1.		0.1	0.7	0.4	3.2	EW	0.51				Local.	
110	June 17, 1.41.41. a.m.	Tremors										Local.	
		Hongō.	0.2	0.8	0.8	6.4	EW	1.20					
111	June 20, 8.38.30. a.m.	Hitotsu-bashi.	0.4	0.9	1.4	9.8	Variable	1.35				NE 70 miles on shore-line, Tokyo on the edge of d. a.	100 miles. Moderately extensive earthquake.

112	June 21, 2. 2.35. p.m.	Tremors					1.05				Local.	
113	June 22, 7.42.39. a.m.	Hongō.	0.2	0.6	1.0	10.0	SN	0.46			E 48 miles on shore-line, Tokyo on edge.	53 m.
		Hitotsu-bashi.	0.3	0.7	1.3	11.2	NW	1.38				
114	June 30, 8. 0.35. a.m.	Tremors										
115	July 2, 3.16.24. p.m.	Hongō.	0.6	0.6	3.1	32.0	S20°E	1.30	Trace		W 45 miles, Tokyo on edge.	55 m.
		Hitotsu-bashi.	0.6	0.9	2.1	14.7	NNE	1.01	Trace			
116	July 4.		0.2	0.9	0.7	4.9	EW	0.32			Local.	
117	July 11, 3. 7.42. p.m.	Hongō.	0.2	0.5	3.1	9.61	SN	0.24				
118	July 22, 8.27. 0. p.m.	Hongō.	1.0	1.4	2.3	10.6	EW	1.38			The same in general features as No. 62 and No. 64. Extensive earthquake.	
		Hitotsu-bashi.	1.9	1.8	3.3	12.1	N30W	3.37				
119	August 15, 0.59.15. a.m.		1.9	2.0	3.0	9.5	SN	3.05	0.1	0.6	1.01	NE 105 miles on shore-line, Tokyo on the edge.	120 m.

Notes.

FOR REFERENCE SEE CORRESPONDING NUMBERS IN THE TABLE AND IN NOTES.

No 1.—This earthquake was moderate in its size, being enclosed within the radius of 47 miles. It affords a good example of both horizontal and vertical motions. The maximum horizontal motion occurred at the third second from the commencement of the shock; at this time the vertical motion was still exceedingly feeble although it was recognizible from the beginning. It reached its maximum 3 seconds later than the horizontal motion which had been then much reduced in its amplitude. The vertical motion was smaller than the horizontal motion in the ratio of 1 to 6; its period was quicker in the ratio of 7 to 8 and its duration of motion was shorter in the ratio of 1 to 3·3. The direction of the maximum horizontal motion was N.N.E. and S.S.W., while the origin of the earthquake lay in due N. from the observing station.

No. 2.—This shock gave the second largest motion recorded in the Table. The horizontal motion was comparatively feeble during the first 20 seconds, but gradually augmented and remained active during 80 seconds. The vertical motion appeared from the beginning, but was very small, notwithstanding the large horizontal movement that accompanied it. The ratio of the former to the latter was 1 to 46 in amplitude, 1 to 4 in period, and 1 to 3·8 in duration.

In this and in the following shocks it will be observed that the direction of the local movement of the ground at the observing station and the direction of the origin of the shock from the city did not generally coincide.

No. 3.—This earthquake disturbed the same portion of the country as No. 2, but with less force. The ground moved almost equally in all directions. More than 120 complete waves, whose periods varied from 0.7 second to 3 seconds, were registered. Notwithstanding the existence of considerable horizontal motion no vertical motion appeared.

No. 4.—This was one of the local shocks which frequently occur in this and in other parts of the country. Its area of disturbance is often not more than a few square miles. The motion is generally feeble in these local shocks.

No. 5.—The ratio of the vertical motion to the horizontal motion was 1 to 10 in amplitude and 1 to 13 in duration.

No. 13.—More than 50 distinct waves of small amplitudes were counted.

No. 14.—This extensive earthquake originated among the mountain districts of Shinano, which is one of the highest portions of the country, 2,000 ft. above the sea level. There is one active and many extinct volcanoes. The seismic waves were not propagated much beyond Tōkyō.

No. 21.—Tōkyō was in the middle of the shaken district.

No. 23.—Both horizontal and vertical tremors were visible from the beginning; but at the fifth second there suddenly appeared a large horizontal motion (maximum). Distinct vertical waves came a few seconds later.[1]

No. 25.—The motion commenced slowly and was not preceeded by quick tremors as is usually the case. The Observatory was comparatively near the origin of disturbance.

No. 33.—This was a middle-sized earthquake in which the observing station was near its origin. The maximum horizontal motion occurred 6 seconds from the commencement, and the maximum vertical motion 2 seconds later. Several distinct vertical waves of the average period of 0·3 second were registered.

No. 39.—Trace of the vertical motion was visible, though the shock was only local and the motion small.

No. 41.—The whole of North Japan was disturbed by this shock, the observing station being near the southern extremity of the disturbed district.

[1] The Jour. Scien. Coll. Vol. I., Plate XI.

No. 47.—The origin, which was inland, was comparatively near the city. There were hardly any vertical tremors during the first few seconds, while there were considerable horizontal tremors. A decided horizontal motion occurred at the beginning of the sixth second; more pronounced vertical motion began one and a half seconds later, and its maximum ocurred several seconds after.[1]

No. 50.—This was another large earthquake, in which the seismic waves were propagated from the origin some 120 miles both north and south, and 61 miles toward the west, where they were stopped by the mountains. On the east they reached the Pacific Ocean. The observing station was comparatively near the origin.

This shock was preceded by tremors of quick period during the first eight seconds, then there suddenly appeared the maximum horizontal motion; at this time the vertical motion, which was visible from the beginning, was yet very small—0·08 mm. with a period of 0.4 second; after 6 seconds it reached the maximum, and continued for eighty-five seconds with decreasing amplitudes and with lengthening periods. The ratio of the vertical motion to that of horizontal motion was 1 to 8·3 in amplitude, 1 to 1·5 in period, and 1 to 2·2 in duration.

No. 51.—This earthquake, although it was quite extensive, and its origin was comparatively near the observing station, produced small motions. The vertical motion was visible from the commencement, and exhibited its maximum at the seventh second when the horizontal motion was also largest.

No. 61.—This extensive shock disturbed the whole of North Japan, Tōkyō being near the edge of the disturbed area. The peculiarity in this shock was the unusually large vertical motion with its slow period.

The ratio of vertical motion to horizontal motion in Hongō 1:2.5
The ratio of vertical motion to horizontal motion, Hitotsubashi 1:6
The ratio of horizontal motion in Hongō to that of Hitotsubashi 1:2.5
The ratio of vertical motion in Hongō to that of Hitotsubashi 1:2

[1]The Jour. Scien. Coll. Vol. I., pl. IX.

No. 62.—Originating on the shores of the Japan Sea, the shock crossed the whole breadth of the main island. Nearer the origin the motions were very violent and somewhat destructive; it stopped the flow of springs and shattered houses.

No. 64.—In general features this shock resembled that of No. 62. It disturbed the same parts of the country and likewise caused considerable damage, though in less degree.

No. 67.—Vertical and horizontal motions began at the same moment, but the maximum of the latter preceded that of the former by several seconds.

No. 72.—Tōkyō was comparatively near the origin.

No. 75.—Tōkyō was near the edge of the disturbed area. The maximum horizontal and vertical motions were simultaneous.

No. 76.—Tōkyō was near the outskirts of the affected district.

No. 77.—It was quite a strong shock nearer its origin, which was in the sea not far from the shore. The maximum vertical motion arrived several seconds before the maximum horizontal motion.

No. 83.—Vertical motion was comparatively large considering the smallness of the horizontal motion; moreover it was clearly pronounced, exhibiting eight distinct waves. Its maximum appeared a few seconds after the horizontal maximum.

No. 85.—This is one of the two largest earthquakes in 1887. The origin of the shock was in S.W. about 35 miles from the Observatory. The seismic waves extended nearly 200 miles to the west and north-east along the Pacific sea-board. On the north-west they approached to the shores of the Japan Sea. They shook, in all, about 32,000 square miles of land area.

At Hitotsubashi, after a few seconds from the commencement of the shock the ground moved suddenly 3 mm. toward the west. At the thirtieth second the maximum horizontal motion recorded in the Table was observed, which apparently cor-

responded with the maximum horizontal motion in Hongō. More than sixty distinct shocks were recorded.

At Hongō, the earthquake commenced with quick tremors. During the third second there appeared for the first time a vigorous horizontal motion in N.W. and S.E. (*i.e.* at right angles to the line joining the origin of the disturbance and the Observatory) accompanied by a considerable vertical displacement. The maximum vertical motion occurred at the ninth second. The maximum horizontal motion occurred at the thirty-third second.

Decided vertical and horizontal motions simultaneously occurred at the second second.[1]

The ratio of the max. h. m. in Hongō to that of Hitotsubashi	1:3
The ratio of the max. v. m. in Hongō to that of Hitotsubashi	13:18
The ratio of the max. v. m. to max. h. m. in Hitotsubashi ...	1:12
The ratio of the max. v. m. to max. h. m. in Hongō	1:6

No. 95.—Tōkyō was on the edge of the disturbed area. There were a few distinct vertical waves at Hitotsubashi.

SUMMARY OF RESULTS.

The results obtained from a study of the preceding table may be summarised as follows :—

In most of the earthquakes vertical motion did not appear, that is, the ground moved entirely in a horizontal plane. This was on account of the origin of the disturbance being far away from the observing station. In the above table, if we reject the slight shocks marked *tremor*, and the doubtful cases, we see that out of 100 earthquakes vertical motion occurred in 28 only, *i.e.*, once in 3.6 shocks.

Taking averages of all the quantities involved in these 28 cases, we find :—

Maximum horizontal motion	1.2 mm.
Complete period of maximum horizontal motion	1 sec.
Duration of horizontal motion	124 sec.
Maximum vertical motion	0.18 mm.
Complete period of maximum vertical motion	0.56 sec.
Duration of vertical motion	42 sec.

[1] Trans. Seis. Soc. Vol. XI., p. 176, pl. I.

Treating similarly the horizontal motion in 95 earthquakes recorded at Hitotsubashi (soft soil), we find :—

Maximum horizontal motion	0.73 mm.
Complete period of maximum horizontal motion	0.96 sec.
Duration of horizontal motion	117 sec.

Also from a like treatment of the horizontal motions in 18 earthquakes recorded at Hongō (hard ground), we get :—

Maximum horizontal motion	0.37 mm.
Complete period of maximum horizontal motion	0.76 sec.
Duration of horizontal motion	74 sec.

The values of the horizontal motion given in the first tabulated set of averages are larger than those in the second and third. The reason is, clearly, that shocks containing vertical motion are generally larger than those without, so that the second and third sets, which include shocks both with and without vertical motion, naturally give smaller averages.

Although the second and the third sets, referring as they do to different shocks, are not strictly comparable, they nevertheless show in a general way that in hard ground the motion is smaller, the period quicker, and the duration shorter, than in soft soil. Their ratios are 1 to 2, 1 to 1.3, and 1 to 1.5 respectively.

In the above sets of averages the records of the somewhat destructive earthquake of January 15th, 1887, were not included, as that was much larger than the ordinary shocks we are dealing with. For the sake of comparison the characteristics of that shock as registered at Hitotsubashi are now given :—

Maximum horizontal motion	21 mm.
Complete period of maximum horizontal motion	2.5 sec.
Duration of horizontal motion	6 min. 34 sec. (Principal motion 2 min.)
Maximum vertical motion	1.8 mm.
Complete period of maximum vertical motion	0.9 sec.
Duration of vertical motion	98 sec.

For details see No. 85. In the earthquake of October 15th, 1884, a maximum horizontal motion of 42 mm., with a complete period of two seconds, was recorded at the above-named place.

When vertical motion occurred it was invariably smaller than the horizontal motion as is obvious from the first set of averages. The average ratio of the two components of the motion was 1 to 6, or the former was only one-sixth of the latter.

The period of the vertical motion was shorter than that of the horizontal motion their average ratio being 1 to 1·8. That is when the ground made one to-and-fro motion it so performed during the same time nearly two complete up-and-down oscillations. In all the preceding tables the periods of the *maximum* vertical motion are given, but the periods in the other parts of the disturbances were much shorter. They varied from 0·2 second to 0·5 second. Exceedingly feeble tremors of a few seconds' duration generally preceded the principal motions as in the case of the horizontal motions.

The duration of the vertical motion was much shorter than that of the horizontal motion. It occurred invariably during the early stages of the earthquake, and generally ended before the horizontal components. The average ratio of the two durations was 1 to 3, or the horizontal motion continued three times longer than the vertical.

The vertical motion almost invariably appeared when the horizontal motion had reached 1 mm. which was more than the average amplitude in ordinary earthquakes. Out of 100 shocks there were 18 cases in which the ground moved more than 1 mm. Out of these 18 earthquakes vertical motion occurred in 14 cases or 78 per cent., and did not appear in the remaining 4 cases.

But, on the other hand, vertical motion also appeared in certain cases when the horizontal motion was less than 1 mm. Out of the 28 shocks already specified as showing vertical motion, 14 showed a horizontal motion of more than 1 mm. while in the other 14 cases the horizontal motion was less than 1 mm.

Again, when we analyze the 14 cases which had vertical motion with less than 1 mm., we see that in 9 shocks the observing station was in, or comparatively near to, the centre of the disturbed districts, and in the remaining 5 cases it was at a considerable distance from the origin. In other words, vertical motion generally appeared when the origin of the disturbance was near the observing station. In such a case the vertical motion might have come directly through the earth-crust from the origin, and not in the form of free surface waves. It must be, however, noted that there were 4 cases in which the observing station was comparatively near the centre of disturbance, but in which vertical motion did not occur. They were all small shocks, with maxmium motions less than 1 mm.

In earthquakes showing both horizontal and vertical motions, feeble but quick-period tremors of both types simultaneously preceded the principal movements. The more decided and pronounced motion usually appeared first in the horizontal component, and then came the large vertical movements.

Tremors, or quick-period minor waves, generally precede earthquakes proper, and their probable connection with sound phenomena has been discussed in this country by Professors Ewing,[1] Milne,[2] and Knott.[3] The vertical motions which have just been considered possess in great measure the characteristics of these minor tremors.

It is a well-known fact that the movement of the ground at the time of earthquakes is very complex, and that the ground moves in all azimuths during prolonged shaking. In the earthquakes discussed in the present paper the direction and the distance of the origin of disturbance from the observing station were known, as also the direction of the maximum movement of the ground. No definite relation between these directions can be established. Seismic waves indeed must suffer much reflec-

[1] Memoirs on Earthquake Measurements, p. 11.
[2] Earthquake Notes—Sound Phenomena, Trans. Seis. Soc. Vol. XII.
[3] Earthquakes and Earthquake Sound, etc., Trans. Seis. Soc. Vol. XII.

tion, refraction, and diffusion as they progress, and the co-existence of normal and transverse waves is a distinct element of confusion.

Out of 119 earthquakes recorded in the tables, 42 were local shocks, which extended only over a small tract of land from a few miles to 10 or 15 miles around. They caused the ground only slightly to tremble, and the horizontal motion of the ground was from 0·1 mm., to 0·3 mm., or even less. There were 4 cases in which the motion reached 0.8 mm. No verctical motion occurred in these local shocks.

There were 119 shocks during the two years, which means more than one shaking per week.

As the continuation of these observations will be published in the coming volumes of this Societys's Transactions, further generalizations or conclusions, that might be deduced from the facts now given, will be reserved for a future paper.

ON CERTAIN SEISMIC PROBLEMS DEMANDING SOLUTION.

By John Milne.

[Read April 20th, 1888.]

1. Sound Phenomena.

On January 26th, I read a short paper before the Seismological Society on the sound phenomena of earthquakes, in which there was an endeavour to show that the sounds which preceeded an earthquake were produced by short period vibrations of the ground forming the front portion of an advancing earthquake. Many earthquakes, like the solar spectrum, have extremities which are difficult to investigate. At the end of an earthquake there are vibrations which are so long in period, that the pointers and steady points of our seismographs do not give a relative movement, but follow these back and forth movements as a whole, and no record is obtained. At the commencement of a disturbance there are exceedingly rapid movements of small amplitude. With indices giving a large multiplication many of these short period movements have been recorded, but if the instrument has a small multiplication they are lost. In all probability these minute movements which have been recorded are the continuation of still smaller and more rapid movements, which on account of want of sufficient multiplication in our instruments have never yet been rendered visible. It is to these hitherto invisible motions that we are to look for an explanation of sound phenomena. Dr. C. G. Knott in his admirable paper on "Earthquakes and Earthquake sounds as illustrating the general theory of vibrations," while discussing the investigations of Lord Raleigh

respecting elastic waves at a bounding surface, points out that certain of the formula indicate that short period vibrations have amplitudes proportionally small.

That period increased with amplitude *up to a certain point* is a fact which has been repeatedly observed, and that it should now be confirmed by theoretical investigation, inasmuch as it tends to harmonize earth motions with those of ideally elastic bodies, is extremely interesting.

It is to vibrations of this description that Dr. Knott looks for an explanation of sound phenomena. They are not so much due to the large movements recorded by seismometers as to minute vertical vibrations which are superimposed upon them or which outrace them. They are true elastic waves. As I understand Dr. Knott, the difference between his explanation and mine is extremely small. He defines the nature of the waves and makes them out to be a phenomenon which may quite be expected to precede the actual earthquake. I advanced the opinion that they were phenomenon with which the earthquake was continuous. In artificially produced disturbances, as in actual earthquakes, short period waves have formed the van of the advancing disturbance. The phenomenon is a curious one, and why it exists is difficult of explanation.

2.—Velocity of Propagation.

If in ordinary earthquakes the movements are beyond the limits of elasticity, it would appear to be a necessity that the disturbance should travel more slowly than if it consisted of true waves of compression or distortion. This is an opinion put forward by Dr. Knott in the above-mentioned paper, and it is an opinion which is probably shared by all scientific men who have thought about this subject.

When we turn to certain observations, and the observations chosen are those which we have every reason to rely upon as being practically accurate, we meet with results which are

difficult to reconcile with the above assumptions. The following are examples of these observations :—

The Charleston Earthquake.

Professor Simon Newcomb and Captain Charles Dutton have subjected upwards of 400 time observations of the Charleston Earthquake to a most rigorous analysis. Many of these observations were obtained by clocks which had been stopped. Many of the clocks being used as regulators had been compared daily with a time signal. A number of the observations specify the time of the first tremors within seconds. The greatest distance over which a wave path was timed was 924 miles. The average distances appear to have been from 300 to 600 miles. According to their relative merits, the observations were divided into 3 groups, the first group containing the most reliable observations. The average results gave the following velocities :—

Group I.	5,205m.	± 168m.
Group II.	5,192m.	± 236m.
Group III.	5,171m.	± 116m.
Average result	5,184m.	± 80m.

(*American Journal of Science*, 30th January, 1888.)

The Destruction of Flood Rock.

In 1885 Flood Rock was destroyed by the explosion of 240,397 pounds of rack-a-rock and 48,537 pounds of dynamite. By specially arranged electrical connections the instant of explosion was noted on chronographs at a number of stations, the farthest being 181.68 miles distant. At each of these stations the arrival of the first tremors were recorded by observers, who watched the disturbance of an image reflected from the surface of mercury. After making various minute corrections to determine the absolute instant of explosion, &c., a series of velocities were obtained. Towards the east through drift, the velocity of the earth wave varied from .83 to 3.15

miles per second, but towards the north, through homogeneous gneiss, the velocity was practically constant, being about 3.88 miles per second, and this for distances of 175 miles. These latter velocities are equivalent to 6,258 meters per second.

The above are examples of the high rates at which earth waves have been observed to be propagated. The highest velocity for a sound wave, through piano steel of density 7.7, is given by Tomlinson at 5,198m. per second.

By cross bending and twisting columns of rock, the writer and Mr. T. Gray determined moduli necessary for calculating the speed with which compressional and distortional waves ought to be propagated. The highest speed calculated was, for a sound wave in granite of specific gravity, 2.63. This was 3,750 metres per second.—(*Quart. Journal, Geological Society*, May, 1883.)[1]

Looking at the four velocities just given, it would appear that the distortional waves of the Charleston Earthquake were propagated through the heterogeneous, and more or less fissured crust of the earth more quickly than a compressional wave is propagated through a specimen of homogeneous granite and practically as quickly as a similar wave is propagated through a piece of steel wire.

The tremors from the Flood Rock explosions, whatever their nature may have been, were propagated more quickly than any of the above waves were propagated.

Amongst other points connected with earthquake motion which are difficult to understand, the following may be enumerated :—

3. In artificial disturbances and apparently in earthquakes, the greater the initial impulse, the greater is the speed of propagation. General Abott showed this to be true in connection

[1] The data on which the above result was founded is unfortunately in England. On receiving the same is will be re-examined.—*J.M.*

with the explosions at Flood Rock, Hell Gate, and many other experiments carried out under his superintendence. The writer showed it to be true for small explosions produced in the alluvium of Tokio.

4. As a disturbance radiates the velocity of propagation decreases. Although many experiments made by General Abott in America and by the author in Tokio have confirmed this conclusion, in the Flood Rock explosion along an easterly course through the drift there was at first an increase in velocity.

5. In soft ground the large horizontal motions are preceded by a series of vertical surface ripples.

6. Near to an origin a normal motion is observed at a short interval before a transverse motion, but as the disturbance radiates the amount of separation between these two components of motion does not increase.

7. Near to an origin the motion inwards towards the origin is greater, and is performed more quickly, than the motion outwards. This may be explained on the assumption that the back swing of the earth is performed in the direction of the crater of explosion which may play the part of a free surface.

8. Near to an origin the amplitude of normal motion is greater than the amplitude of transverse motion, but as the disturbance radiates they rapidly approximate to each other.

9. At any given station the period becomes longer as the disturbance dies out.

10. As a disturbance radiates the period becomes longer.

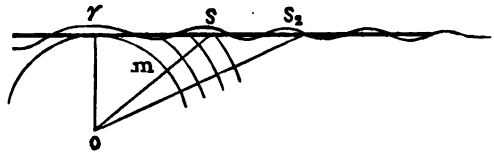
11. For *small* displacements the period increases with the amplitude.

12. As a given vibratory motion radiates from the origin it may split up into two waves.

For a detailed account of the observations which have led to the above conclusions see "Seismic Experiments," *Trans. Seis. Soc.* Vol. VIII.

RADIATION OF A DISTURBANCE IN THE EARTH'S CRUST.

The following remarks upon the manner in which an earthquake may radiate are chiefly based upon observations and the results of experiments :—



If an impulse originates at a centre O, the experiments of military engineers have shown that the radius rs of a crater which might be found never exceeds three times the line of least resistance ro. Providing the initial impulse at o is sufficiently great, inside the circle rs a direct shock resulting in projection may be experienced. A direct shock due to waves of compression might also be felt as far as some point s_2. Assuming o to be surrounded by spherical shells each the breadth of the vibration of a particle, the energy of a particle k_1 in a shell of radius r_1 will be to the energy of a particle k_2 of a particle in a shell of radius r_2, inversely as the cubes of the radius of the shells, or

$\frac{k_2}{k_1} = \frac{r_1^3}{r_2^3}$, and as energy is dissipated $\frac{k_2}{k_1} = f\frac{r_1^3}{r_2^3}$ when f is less than unity and represents the rate at which energy is dissipated.

From this it would appear that within the crust of the earth the energy of the initial impulse must be dissipated at a very rapid rate and the distance at which a direct shock is felt is probably very small. Whatever intensity may be recorded at a point s an equal intensity will be found for downward directions at points nearer to o than os, that is to say, owing to the movement of particles being more constrained in the interior of the earth than at the surface, energy is dissipated more quickly in the interior than along the surface.

Apart from these theoretical considerations, it has been found

by experiment that the movement at points near to *r* but outside the crater of disruption, the vertical component of motion, cannot be accounted for as being due to a direct wave of compression. The vertical movements are free surface waves which can be felt. In large earthquakes they have often been seen, and for artificial disturbances if not also for actual earthquakes they have been instrumentally recorded. Their velocity of propagation is very great. They are probably produced by the outcrop of the waves of compression near the origin, and at a distance from the origin it may be only these waves which are sensible.

Mallet,* who speaks of such waves as probably forming the front portion of all earthquakes, refers to the experiment of Wertheim and Breguet on the linear and transversal vibrations of wire, which are propagated at values in the ratio of 3485 : 4634. (*Compus Rendus*, t. XXXII., p. 293.)

As these free surface waves apparently travel more quickly than compressional waves, it would seem that even at a station within the cone of direct shock, excepting at *r*, these free surface waves may be felt first and might be sufficiently large to mask the direct waves of compression.

Another point of importance is the fact that the amplitude of direct motion decreases very rapidly as a disturbance radiates, and therefore at a distance from the origin the direction of motion may be equally in any many azimuth.

* *Neapolitan Earthquake* Vol. II. p. 300.

EARTHQUAKES AND EARTHQUAKE SOUNDS:

AS ILLUSTRATIONS OF THE GENERAL THEORY OF ELASTIC VIBRATIONS.

By CARGILL G. KNOTT, D. Sc. (EDIN.), F.R.S.E.

(Read February 23rd, 1888.)

The first systematic application of the theory of vibrations to the problems of earthquake motion was made, I believe, by Hopkins in his Report on the Theories of Elevation and Earthquakes, presented to the British Association in 1847. During the forty years which have elapsed since then, our knowledge of earthquake phenomena has steadily grown. The labours of Mallet have been largely supplemented by the observations and experiments of a small army of enthusiasts, who have pitched their tents on the trembling soil of Italy and Japan. Their energies have been mainly directed to the perfecting of seismographs and seismometers, to the registering of all kinds of earth movements, to the study of the effects of these on buildings, and, in a limited degree, to the measurement of the velocities of propagation of disturbances due to artificial earthquakes. With all this activity on the experimental side, we have to confess that theoretic views have hardly advanced beyond the stage in which Hopkins left them in 1847. G. H. Darwin's discussion of the strains due to continental areas, and Lord Rayleigh's investigation into a special case of surface waves on an elastic solid, are perhaps the only mathematical pieces of work that have any distinct bearing on seismic phenomena. The former gives an obvious *raison d'être* for the existence of seismically sensitive regions within the earth's crust, but, being an equilibrium problem, can throw no light on that progress of the state of strain which constitutes earthquake

motion. Lord Rayleigh's results will be referred to hereafter in due course. Meanwhile, as it is my object to discuss in a general way how far earthquakes and their accompanying effects may be explained as disturbances in an elastic or sub-elastic medium, it will be convenient to reproduce here much that may be found in authoritative earthquake literature, such as Hopkins' and Mallet's *Reports*, Mallet's *Neapolitan Earthquake*, Milne's *Earthquakes*, and so on.

From the general theory of the vibrations of homogeneous elastic solids we know that there are three types of wave propagated with different velocities. If we confine our attention to an isotropic elastic solid these types reduce to two, which are kinematically easily distinguished by the relation which the direction of vibration of any particle bears to the direction of propagation of the wave. Thus in the one type the vibrations are *normal* to the wave-front—in the other they are *transverse* or *tangential*. Dynamically the types may be distinguished as the *condensational* and *distortional* waves. The former is of essentially the same character as ordinary sound waves in air; and the latter may be compared, so far as direction of motion is concerned, to waves of light in the luminiferous ether. In the condensational wave the vibrating particles move to and fro in lines parallel to the direction of motion of the wave. In the distortional wave, the particles move to and fro in lines perpendicular to the wave's direction of motion.

In all cases these two types of wave are propagated with different velocities, which depend upon the density and the elastic constants of the material. For an isotropic elastic solid there are two independent elastic moduli, known respectively as the *bulk-modulus* or resistance to compression, and the *rigidity* or resistance to distortion. The velocity of the distortional wave depends on the ratio of the rigidity to the density. The velocity of the condensational wave, however, is not so simply related to the other modulus, but depends for its value upon the rigidity as well.

Take for example a uniform cylindrical rod of iron. By giving the one end of this rod a slight twist we may set up a series of torsional vibrations, whose velocity of propagation along the rod is to be measured by the square root of the ratio of the rigidity to the density. The velocity of propagation of longitudinal vibrations, which may be supposed to be given by an impact on the end, is to be measured by the square root of the ratio of the so-called Young's Modulus to the density. Young's Modulus is a definite function of the principal moduli already mentioned, being given by the formula

$$9\,n\,k\,/\,(3\,k + n)$$

where k is the resistance to compression and n is the rigidity.

Again, if we consider the case of plane waves in an infinite solid, we find that here also the velocity of propagation of the distortional wave is given by the ratio $\sqrt{n}/\sqrt{\rho}$, while that of the condensational waves is measured in terms of a mixed modulus which is not necessarily the same as Young's Modulus. Its value is $k + \frac{3}{4}\,n$ which is equal to Young's Modulus only if $3\,k = 2\,n$.

According to Navier's and Poisson's theory of elasticity, we should have $3\,k = 5\,n$. This is usually expressed by saying that, if a bar is stretched under a longitudinal pull, its linear contraction at right angles to the pull is one quarter of the elongation in the direction of the pull. So far as experiments with hard metals go, this ratio may vary from .2 to .4. Nevertheless .25 may be taken to be a pretty fair mean value.

If we write m instead of $k + \frac{3}{4}\,n$,* we obtain for the value of the Poisson ratio the expression

$$s = \frac{m - 2\,n}{2\,(m - n)}$$

The possible values of s range from $+\frac{1}{2}$ to -1;—the former being its value in an incompressible elastic body, the latter its value in a body of infinite rigidity but finite compressibility. The

* This m is not the same as the m used by Thomson and Tait, but for our present purpose it is convenient to use one symbol for the mixed modulus which determines the speed of the condensational wave.

luminiferous ether appears to be a substance of infinite resistance to compression; but of the other limiting kind of elastic material we have no example.

The velocities of the condensational and distortional waves are given respectively by the expressions $\sqrt{m/\rho}$ and $\sqrt{n/\rho}$, ρ being the density of the material.

There are experimental methods for measuring the quantities m and n; and from them the two velocities can easily be calculated. Or if the two velocities are known, it is possible to calculate from them the two moduli. Now, it is quite obvious that m must always be greater than n; the ratio indeed varies from ∞ for the case of the incompressible body to $4/3$ for the case of the infinitely rigid body. Of course in the latter case both waves travel with an infinite speed; but the speed of the distortional wave can never become equal to the speed of the condensational wave, however large it is made to be.

In deducing the true values of m and n from the two wave velocities, we must know the density of the material. The only values for wave-velocities of both types in rocks, which I have been able to find, are those given by Messrs. Milne and Gray. These velocities were originally obtained from direct measurements of the elastic moduli of the rocks in question. The moduli themselves Professor Milne has recently furnished me with. In the following table they are given,* expressed in C.G.S. units, along with the Poisson ratio s.

Rock.	m.	n.	s.
Granite ...	4.68×10^{11}	1.44×10^{11}	+ .28
Marble.....	4.35×10^{11}	1.3×10^{11}	+ .29
Tuff	2.44×10^{11}	1.31×10^{11}	— .08
Clay Rock..	3.66×10^{11}	1.94×10^{11}	— .07
Slate.....	6.07×10^{11}	2.45×10^{11}	+ .16

* In the notes given me by Professor Milne the numbers here tabulated under m are headed "Young's Modulus." This, I am inclined to think, is a mistake. Professor Milne himself, not having the complete records in possession, is doubtful. At any rate, these numbers give the velocities of the normal vibrations as tabulated by Messrs. Milne and Gray (see *Phil. Mag.* November, 1881). Further, if they really were Young's Moduli, we should have in granite and marble examples of substances which expand when compressed!

Two of the ratios come out negative, which means physically that, if the substance is perfectly elastic, an extension of the substance by a pull in a given direction is accompanied by an extension at right angles to this direction. It also means that the ratio of the velocities of the two waves is distinctly smaller than in the other cases. This diminished ratio, it will be noticed, exists along with a diminished resistance to compression, while the rigidity continues to have much the same value as those which hold for the other rocks. In the cases of the tuff and clay-rock we may have to do with either a considerable compressibility, or a sluggishness in recovery due to the viscosity of the material. Such a viscosity might well show itself more distinctly in compression than in distortion.

If we calculate from Professor Milne's values of wave velocities obtained from his experiments on artificial earthquakes, we find for the ratio s in two different cases the values $+.154$ and $-.152$ and for the corresponding ratios of m to n the values 2.43 and 1.76.

In the calculations to be described presently, I have taken the following values of the several constants involved as a fair approximation to what might reasonably be regarded as somewhat near the truth, when the elastic properties of fairly solid rock are to be considered.

density ..... ρ	$= 3$
rigidity ..... n	$= 1.5 \times 10^{11}$
ratio of the wave-moduli ..... m/n	$= 3$
Poisson's ratio ..... s	$= .25$

We now pass to the consideration of the transmission of waves in an elastic solid; and first I desire to call attention to Lord Rayleigh's short paper "On Waves Propagated along the Plane Surface of an Elastic Solid."*

* Proceedings of the London Mathematical Society (Vol. XVII., 1885-6.)

To show that the paper deserves the special attention of members of the Society I need but quote the two concluding sentences. "It is not improbable that the surface waves here investigated play an important part in earthquakes, and in the collision of elastic solids. Diverging in two dimensions only, they must acquire at a great distance a continually increasing preponderance"—that is, I presume, as compared to waves diverging in three dimensions.

The purpose of the paper is "to investigate the behaviour of waves upon the plane free surface of an infinite homogeneous isotropic elastic solid, their character being such that a disturbance is confined to a superficial region of thickness comparable with the wave length. The case is thus analogous to that of deep-water waves, only that the potential energy here depends upon elastic resilience instead of upon gravity."

Starting with the usual equations of motion of a vibrating elastic solid, Lord Rayleigh obtains a general solution on the assumptions that the displacements are harmonic functions of the time and the two co-ordinates parallel to the plane free surface, but are exponential functions of negative multiples of the distance from this plane. The boundary equations are then introduced; and from the conditions for the equilibrium of a surface element the various constants of integration are determined in terms of the circumstances of the assumed motion. Two cases are discussed in detail—those, namely, of an incompressible elastic solid and of a solid for which the Poisson ratio has the value one-fourth. For both cases the results are very similar. Thus, if the displacements are supposed to be confined to one plane, a particle at the surface moves in an elliptic orbit whose major axis is perpendicular to the plane surface of the solid. For the incompressible solid the major axis is nearly twice as great as the minor axis; and for the other case it is about one and a half times as great. The displacement parallel to the plane surface penetrates but a short distance into the solid—to about one-eighth of a wave-

length for the incompressible substance, and to about one-fifth for the other case. On the other hand, there is no finite depth at which the motion perpendicular to the plane vanishes. The surface waves are propagated at a slightly slower rate than a purely distortional plane wave would be.

It would appear then that vertical motion on a level surface over which a disturbance is passing cannot exist alone. Associated with it there must always be a distinctly smaller horizontal motion, which vanishes completely at a short depth below the surface. Lord Rayleigh's formulæ also show that the amplitude of the displacement is directly as the wave-length; so that for vibrations of short period the surface motions are proportionally small.

If we consider the features of earthquake motions, we find that the vertical motion when it is appreciable is always very much smaller than the horizontal motion. Hence we cannot have here merely the surface disturbance discussed by Lord Rayleigh. If his investigation touches upon any earthquake phenomenon, this phenomenon is never met with by itself alone. Horizontal displacements exist, at any rate along with it, of a magnitude greater far than Lord Rayleigh's result requires. The simple conclusion is that ordinary earthquakes cannot be regarded as due to the propagation of surface waves. Professor Milne has, at various times, speculated upon the existence of such surface-waves outstripping the vibrations transmitted through the mass. There never has seemed to me sufficient reason for calling in the aid of these surface-waves, as distinct from the mass-waves. Lord Rayleigh's investigation shows besides that the velocity of a surface disturbance is somewhat less than the velocity of the distortional plane wave travelling through the mass. There is no evidence of a quickened velocity. These two facts, namely, the comparative minuteness of the vertical motion in all earthquakes, and the somewhat slower speed of Lord Rayleigh's surface wave, seem to show that we can expect very little towards the elucidation of earth-

quake phenomena by taking into account the so-called surface wave.

I now pass to the consideration of the reflection and refraction of plane waves at the surface of separation of two elastic media. In doing so I shall direct more especial attention to the case in which the one medium is rock and the other water. The case in which both media are solid substances is a good deal more troublesome to deal with; and so far I have not had time to work out any detailed calculations concerning it. A few general considerations will show the nature of the problem.

The reflection and refraction of plane waves at the bounding surface of two media have been very closely studied by many mathematicians. Especially have their efforts been directed towards the explanation of the ordinary phenomena of light upon a purely dynamic basis. Cauchy, Green, Maccullagh, Lorenz, Rayleigh, Thomson, may be mentioned in this connection. It is sufficient here to point out that, when the problem is worked out for the case of two incompressible elastic substances of equal rigidities but different densities, results are obtained in fair accordance with observation. The media being incompressible, no wave of condensation can be propagated through them. Distortional waves only can exist. Thus an incident distortional wave falling on the bounding surface will, in general, be broken up into two waves, one reflected into the first medium and the other refracted into the second medium. But although distortional waves alone exist in the media, the correct solution of the problem in elastic solids requires us to take account of something existing at the bounding surface of the nature of a condensational wave. We must bear in mind, indeed, what the physical meaning of incompressibility is. It is not that the condensational wave vanishes but that it is transmitted with infinite velocity. By taking this surface disturbance into account—this *pressural* wave as Thomson has called it—we are able partially to explain certain

phenomena of reflection and refraction of polarised light in terms of the theory of elastic solids.

Now in this special problem we begin with a distortional wave incident on the bounding surface; and, although the media are taken as incompressible, we must not neglect the effect of the pressural wave. Hence, if our methods of attack are to be the same in all cases, we must admit the possibility of true waves of compression being started in media of finite compressibility, when upon their boundary a single distortional wave impinges. In other words, an incident distortional wave may be broken up into four parts;—a reflected distortional, a refracted distortional, a reflected condensational, and a refracted condensational. In like manner, an incident condensational wave will in general give rise to reflected and refracted distortional waves as well as to reflected and refracted condensational waves.

The various angles of reflection and refraction are easily calculated in terms of the angles of incidence, it being noted that the surface trace is common to all the waves. In other words each wave velocity is, so to speak, the component in its direction of the velocity of propagation of the surface trace.

Thus, let a condensational wave be incident at an angle θ to the normal to the bounding surface; let m, n, ρ, and m', n', ρ' be the wave moduli and densities of the two media, in the first of which the incident wave is given. Then if θ' be the angle of refraction of the condensational wave, and ϕ ϕ' the angles of reflection and refraction of the distortional wave, the above condition gives these equations:—

$$\frac{m}{\rho}\operatorname{cosec}^2\theta=\frac{n}{\rho}\operatorname{cosec}^2\phi=\frac{m'}{\rho'}\operatorname{cosec}^2\theta'=\frac{n'}{\rho'}\operatorname{cosec}^2\phi'$$

Now, as n is less than m, there will always be a reflected distortional wave, except of course at normal incidence when $\theta=0°$, or at grazing incidence when $\theta=90°$. There will be refracted waves at all except the limiting incidences if m/ρ is greater than m'/ρ'. If m/ρ should be intermediate in value between m'/ρ' and n'/ρ' there will always be a refracted dis-

tortional wave, but for angles of incidence higher than a certain critical value a refracted condensational wave is impossible. Further if m/ρ should be less than n'/ρ', then, for each refracted wave, there is a special critical angle of incidence at and above which the wave vanishes. When the critical value corresponding to the refracted distortional wave is reached, there will be total reflection, and the whole energy of the incident wave will be divided between the two reflected waves.

If the incident wave is a distortional wave, there must always be a critical angle of incidence for and above which the reflected condensational wave vanishes. The existence of such critical angles for the refracted waves will depend upon the relative values of the quantities n/ρ, m'/ρ', n'/ρ',—the condition for the possibility of total reflection being that n/ρ is less than n'/ρ'.

If one of the media is a fluid, there can, of course, be no distortional wave in it. It is this somewhat simple case I propose to discuss in detail. I shall not here enter into the purely mathematical method by what the energies of the various possible waves have been determined. It is sufficient to say that it is the usual mode of treatment of plane waves, a harmonic form being assumed and the constants determined so as to satisfy the equations of motion and the boundary conditions.

We shall take then, as the one medium, water; and, as the other, rock of density 3, rigidity 1.5×10^{11} and Poisson ratio .25. The density of the water is taken as unity and the value of the bulk-modulus, which in this case is also the wave-modulus, 2.2×10^{10}. The quantities are given in C.G.S. units. The manner in which, for different angles of incidence in the rock, the energy of the incident wave is distributed amongst the reflected and refracted waves is shown in the following tables. The first refers to the case of the incident wave being condensational; the second to the case of the incident wave being distortional. The quantities A A_1 A' re-

present the energies of the incident, reflected and refracted condensational waves; B B_1 B' the energies of the similar set of distortional waves. The corresponding angles of incidence, reflection and refraction are given in contiguous columns—θ referring to the condensational and ϕ to the distortional waves.

INCIDENT WAVE CONDENSATIONAL.

INCIDENT.		REFLECTED.	REFRACTED.		REFLECTED.	
θ	A	A_1	θ'	A'	ϕ_1	B_1
0°	1	·599	0°	·401	0°	·000
10°	1	·536	3° 49′	·397	5° 45′	·071
20°	1	·377	7° 32′	·370	11° 23′	·254
30°	1	·195	11° 2′	·333	16° 35′	·456
40°	1	·056	14° 15′	·293	21° 47′	·660
50°	1	·006	17° 4′	·244	26° 15′	·753
60°	1	·014	19° 22′	·206	30°	·775
70°	1	·031	21° 5′	·188	32° 51′	·783
80°	1	·000	22° 9′	·182	34° 39′	·818
89°	1	·616	22° 31′	·069	35° 16′	·314
90°	1	1		·000		·000

INCIDENT WAVE DISTORTIONAL.

INCIDENT.		REFLECTED.	REFLECTED.		REFRACTED.	
ϕ	B	B_1	θ_1	A_1	θ'	A'
0°	1	·1	0°	·0	0°	·0
10° 23′	1	·711	20°	·253	7° 32′	·036
21° 47′	1	·222	40°	·656	14° 15′	·126
30°	1	·014	60°	·779	19° 22′	·206
34° 39′	1	·027	80°	·815	22° 9′	·157
35° 16′	1	·679	89°	·311	22° 31′	·007
35° 16′	1	1	90°	·000	22° 31′	·000
36°	1	·584			22° 56′	·415
40°	1	·461			25° 14′	·539
50°	1	·504	non-existent.		30° 33′	·495
60°	1	·506			35° 4′	·494
70°	1	·520			38° 34′	·480
80°	1	·634			40° 47′	·366
89° 45′	1	·818			41° 34′	·183
90°	1	1				·000

In the first table B and B' of course do not appear; and in the second table A and B' do not appear.

It should be mentioned that each wave energy is calculated independently; and a test of the accuracy of the calculations is afforded by the condition that the energy of the incident wave must be fully accounted for. That is, since, in every case the incident wave (either A or B) is taken as unity, the sum of all the others must also be unity.

The chief peculiarities embodied in these tables are shown graphically in the corresponding curves. Any one curve represents the manner in which the energy of each wave depends on the angle of incidence. The angles of incidence are measured off along the horizontal line; and the corresponding energies are represented by the ordinates perpendicular thereto. The energy of the incident wave is of course represented by a straight line at unit distance from the line along which the angles of incidence are measure off.

The first set of curves shows the state of things for an incident condensational wave. For the sake of brevity, we shall occasionally refer to the different waves by the letters A A_1 A' B B_1 chosen to represent their energies. At perpendicular incidence condensational waves only are started at the bounding surface; and as the angle of incidence increases the energies of both of these diminish. A', which we may also call the water wave, seems to fall off continuously until it vanishes at grazing incidence. The A-wave, however, vanishes at two distinct incidences, and after 80° is reached begins to increase till at 90° it attains unity. The behaviour of this reflected condensational wave is extremely curious, being indeed practically non-existent for incidences between 50° and 80°. The greater part of the energy of the incident wave is then accounted for by the B_1 or reflected distortional wave. For incidences higher than 45°, three-quarters of the whole incident energy is so transformed. It will be noticed that up to pretty high angles of incidence the water-wave does not suffer any very rapid falling off.

Turning now to the second set of curves, which show the state of things for an incident distortional wave, we meet with some very curious relations. For reasons already discussed, the A_1-wave cannot exist for incidences higher than a certain critical value, which depends only on the rock itself. This wave however attains a considerable maximum value for an angle of incidence slightly below this critical value. Almost for the same incidence, the B_1-wave falls to a very low minimum, almost vanishing indeed. Comparing this first portion of the second set of curves with the first set of curves as a whole, we see a general resemblance between the two. That is, the reflected wave of the same type as the incident wave rapidly falls off to a minimum, as the angle of incidence grows, while the reflected wave of the other type rapidly increases to a maximum. Finally, however, the reflected wave of the same type, in both cases quite abruptly, runs up to equality with the incident wave. In the second set of curves this happens at the angle of total reflection; for, not only does the A_1-wave vanish, but so also does the A'-wave *—which indeed never attains any great significance at the lower incidences. After the critical angle of incidence is passed, however, the A'-wave soon reaches a maximum, being then of greater importance than the B_2-wave, and gradually falls away to zero, while the B_1-wave as gradually rises to unity.

In trying in some way to bring these results into correspondence with earthquake phenomena, we notice first of all that, if an earthquake is to be regarded as a progressive wave in an elastic solid, the angles of emergence of the waves will generally be small—that is, the angles of incidence large. Hence we need pay but little attention to the state of affairs at the lower incidences. For higher incidences we see that whether the incident wave is condensational or distortional, the energy is reflected either wholly or almost wholly in the

* This seems to be a result as novel as it is curious from a purely theoretical point of view, although it has no special bearing on earthquake phenomena.

distortional wave form. Suppose for example that a disturbance begins at some region below the bottom of the sea, say at the point *C* in the figure; and let us assume that what starts from *C* is a simple wave of compression—that is a condensational wave. Then to any point *P* suitably placed, there will come not only a purely condensational but also a distortional wave produced by reflection from some part of the surface separating the sea and the land.

It is easy to see, however, that this transformation of condensational into distortional straining will accompany all similar cases of reflection at the boundary of two different media, whether the one medium is water or some other substance—air, say, or mud, or rock. Also we may safely assume that during *refraction* across a boundary separating two media, both being of the category of elastic solids, an incident condensational wave will give rise to a distortional as well as to a condensational refracted wave. In the light of these results, then, it is little wonder that no definite relation has ever been shown to exist between the manner of motion of a particle and the direction of propagation of an earthquake. I should also be inclined to regard as absolutely futile any attempt to infer the nature of the movement in which the shock originates from the nature of the motion of any surface particle.

Even in the extremely simple case of an isotropic elastic solid, we see how a single reflection (and probably refraction) is sufficient to alter the type of wave motion, or rather to bring into existence the other type. How much more will this be true in such a heterogeneous mass as we know the earth's crust to be! And if the large earth shiftings, which certainly mean straining beyond the limits of elasticity, differ essentially from the purely elastic disturbances we have just been considering, it will not be in the direction of simplicity.

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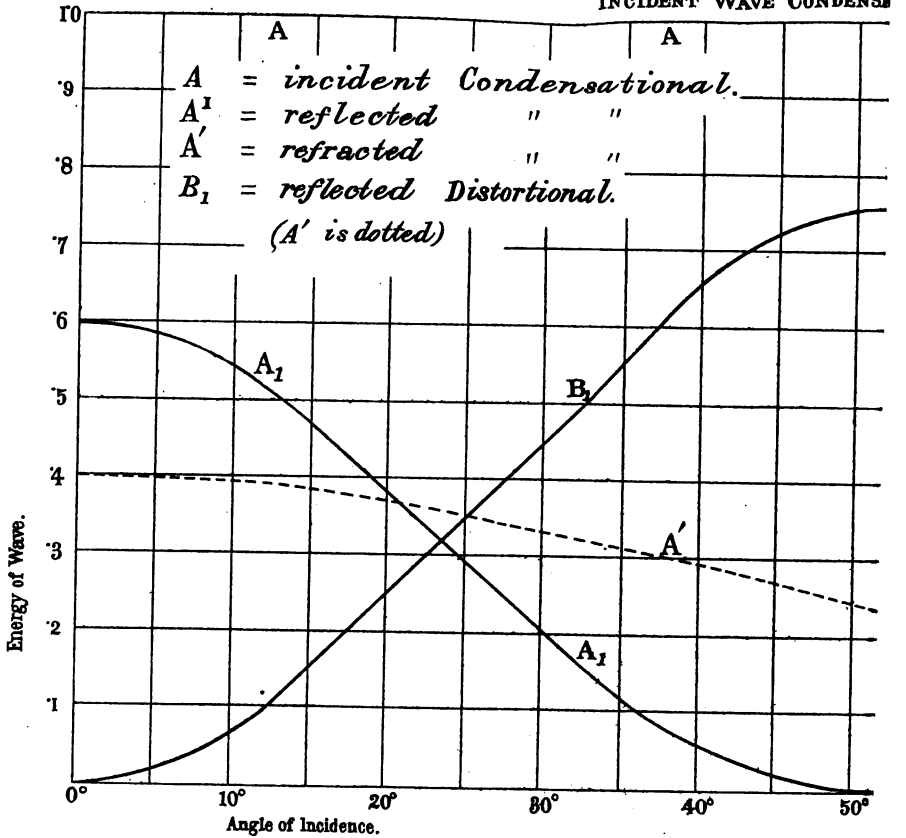

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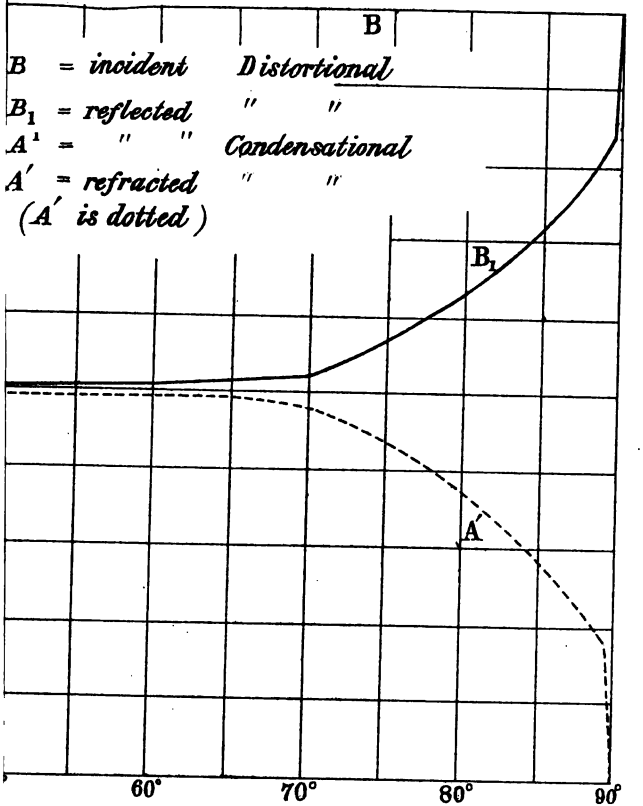

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It seems reasonable to expect in these also somewhat analogous, although much more complex, relations. Hence it may safely be concluded that the existence of distortional or transverse waves does not of necessity imply a *faulting* of rocks, any more than that the existence of the other type necessarily points to a *rupture* or an explosive increase of pressure. In short, as observation has only too plainly demonstrated, it seems vain to look for any certain separation of the normal and transverse types of vibration. Only when the origin of the disturbance is within a few miles of us, and is at an insignificant depth below the earth's surface, can we reasonably expect to find an appreciable separation of the two types of waves.

At this stage we may very fitly consider the general import of the assumption of the existence of these two types of wave in earthquake motion. The assumption is tantamount to regarding the earth's crust as isotropic. Such a characteristic may safely be applied to surface soil; so that, in artificial earthquake experiments, such as Professor Milne has carried out, it may be an easy matter to distinguish the normal vibrations as their wave outstrips that of the transverse vibrations. But it is altogether out of the question to regard any stratified rock as isotropic; while, as for non-stratified rocks, their heterogeneity makes a theoretical discussion of their elastic properties impossible. By consideration then of the elastic properties of homogeneous isotropic media, we can only hope to get at best a glimpse into the seismic darkness. And small though the present contribution may be to the vast problem of earthquake motion, it surely will have some value if only it opens our eyes to the vanity of expecting the study of surface motions to throw much light on the question of earthquake origin.

And now let us pass to the discussion of the refracted water-wave. Here a glance at the two sets of curves shows that the incident distortional wave is, at the higher incidences, much more efficient than the condensational wave in creating a progressive disturbance in the water. The angle of refrac-

tion can never exceed 42°; so that even for very high incidences the water wave will travel upwards to the surface tolerably directly. Here I think we may have the explanation of the curious bumpings which have sometimes been felt at sea. These must not be confounded with the tidal waves so frequently the companions of earthquakes, and due almost without a doubt to large displacements of the ocean bottom. What I refer to here are the jerks or shakings (sometimes accompanied by sounds) discussed by Professor Milne in the opening paragraph of Chapter IX. of his book on *Earthquakes*. Sounds of course will be heard if the periodic time of any of the components in the wave motion is short enough, and if at the same time the intensity is sufficient to give rise to *audible* sound waves in the air, either directly, or indirectly through the medium of such a solid as a ship. According to Colladon's experiments at the Lake of Geneva, the speed of sound in water at 8°.1 C. is 1435 metres per second. This gives 14·35 metres (or about 8 fathoms) for the wave-length of a wave whose pitch is 100 vibrations per second. A slower vibration will of course give a longer wave-length; and a quicker a shorter. But enough has been said to show that in such a wave of condensation we have something quite fitted to affect even a large ship as a whole.

Now all that has been said regarding the transference of vibrations from rock to water will, in a general way, hold true of their transference from rock to air. For all angles of incidence in the rock, the angle at which the refracted ray passes out into the air is very small. Thus, returning to the equation

$$\frac{m}{\rho}\,\mathrm{cosec}^{\,2}\theta = \frac{m'}{\rho'}\,\mathrm{cosec}^{\,2}\theta'$$

and giving m', the wave-modulus in air, the value $1{\cdot}41 \times 10^6$, and ρ' the value ·0013, we find, with the same values as formerly for the rock constants,

$$\mathrm{cosec}^{\,2}\theta = {\cdot}00242\ \mathrm{cosec}^{\,2}\theta'$$

Hence of $\theta = 90°$, $\theta' = 2°\ 50'$ nearly.

In the same way, calculating for the incident distortional wave, we obtain

$$\text{cosec}^2\phi = \cdot 00726\ \text{cosec}^2\theta'$$

Hence if $\phi = 90°$, $\theta' = 4° 53'$ fully. Thus, whatever the incidence, the refracted wave goes off in a direction never more than 5° removed from the normal.

Into a detailed calculation regarding the distribution of the energy, it is not necessary to go. The amount of energy which gets into the air as a condensational wave is extremely small compared to the vibratory energy existing in the rock. With the constants as given above it is doubtful if for any incidence as much as the thousandth part of the original energy is so transmitted into the air. For most incidences it is distinctly less.

It is thus easy to see why in earthquakes which may be accompanied by considerable mechanical violence, there may be no audible sound phenomena. The essential condition for the production of earthquake sounds is a sufficiently pronounced vertical motion with a sufficiently rapid period. According to Professor Sekiya's recent analysis,* vertical motion as measured on the seismographs is absent from most of the earthquakes that shake Japan. When vertical motion is apparent, it is in the more intense shocks. We cannot assume of course that the vertical motion is absent in those cases in which the seismograph shows no trace of it. It is always much smaller than the horizontal motion, being on the average only one-sixth of it. Hence when the horizontal motion is itself very small, as in the weaker shocks, the vertical motion may be too small to affect the seismograph. Or, as is more than likely, it may have too short a period to make itself felt, even though its amplitude may be large enough to be otherwise apparent. We must be careful indeed not to confuse the seimograph indications with the rapid elastic vibrations which seem a necessity for the production of sound phenomena.

* See the present volume of Transactions Vol. XII.; also the Journal of the College of Science, Imperial University, Vol. II.

That the quick short period motions that precede the big wave as shown on our seismographs may co-exist along with vertical vibrations sufficiently rapid to cause audible sounds is highly probable; but in no other sense can they be regarded as "connected" with those sounds, as seems to be suggested by Professor Milne. These rapid sinuosities appear on all the best diagrams showing the horizontal motion; but, as, I believe, it is the vertical motion we must look to specially.

Another point brought out strongly by Professor Sekiya's analysis is that in no case has he found the vertical motion precede the horizontal motion. The vertical seems always to show itself later. It is certain, however, that earthquake sounds are often heard before the earthquake shock is felt. This simply means that the big earth shiftings which affect our seismographs are preceeded by rapid vibratory motions which, however large they may be, cannot have any mechanical effect on the instruments. The case is exactly similar to what happens if we pass alternating electric currents through the coil of an ordinary galvanometer. No matter how sensitive the galvanometer, or how intense the alternating current,—so long as the alternation is rapid enough, no effect is observed on the galvanometer needle. So it cannot fail to be with ordinary seismographs as regards rapid vibrations. I doubt if a seismograph, mechanically capable of registering vibrations occurring at even so slow a rate as 10 per second, has been as yet imagined. It is very questionable also if those sinuous records which the seismograph tracings show as precursors of the large slow waves really indicate what is taking place in the soil. For, exactly as very rapid vibrations will not show at all on the seismograph trace, so somewhat less rapid vibrations will not show to their full. There must always be a lagging of the record behind the motion recorded. Thus before a given motion has its full effect on the seismograph, the rapid reverse motion may set in and prevent anything like a complete record. Not until a comparatively slow "swing-swang" of the ground takes place can we hope to have a tracing even ap-

proximately true as to amplitude. It is therefore well, I think, that seismologists should bear this point in mind. It is highly probable that an earthquake is preceded by rapid vibratory motions. That we should expect; and the early sinuosities of earthquake tracings certainly suggest the same. But that these sinuosities can be taken as an approximate representation of the amplitudes or periods of the rapid vibration to which they are due may well be matter of grave doubt.

In conclusion, I would draw special attention to the following point which seems to be of some importance.

In the discussion of the propagation of seismic disturbances through the earth's crust, a clear distinction should be drawn between purely elastic and QUASI-*elastic phenomena.* So long as the materials constituting the earth's crust are not strained distinctly beyond the limits of elasticity, we have to do with purely elastic vibrations. These generally speaking will be transmitted with considerable speed, comparable to that of sound in steel wires. Such high speeds have indeed been observed, their existence depending upon a small compressibility (or high rigidity) combined with a comparatively small density. The destructive effects of earthquakes are, however, due to the propagation of *quasi*-elastic disturbances. In them the material is distinctly strained beyond the limits of elasticity; or, at all events, so strained as to bring about conditions in which other strain-coefficients than the usual ones of rigidity and compressibility play the important part. It is quite to be expected that these *quasi*-elastic disturbances should travel much more slowly than the purely elastic ones. The investigation given above into the effect upon the type of elastic waves as they suffer reflection at the boundary of two isotropic elastic media suggests the existence of analogous effects in the propagation of all seismic disturbances. The aeolotropy and discontinuity of the earth's crust will transform a disturbance of an originally simple type into one or more of excessive complexity. Furthermore, wherever a *quasi*-elastic disturbance suffers transformation at some region of discontinuity, it will give rise to a

new set of elastic disturbances. And again, as the *quasi*-elastic disturbances lose energy per unit volume, partly because of radiation, partly because of dissipation, they will gradually lose their *quasi*-character, and become of a purely elastic nature. It is quite conceivable, then, that under certain circumstances the speed of a disturbance might undergo strange variations, appearing even to be accelerated as its intensity diminished. Such a phenomenon was observed by Lieut. Col. Abbot at Flood Rock explosion in 1885. Of course a peculiar change of this kind might easily be due to the different elastic properties of successive portions of rock travelled through. It is quite possible, however, that the other explanation is the true one. It is known that a very intense sound travels faster in air than one of less intensity; and the same will be true of vibrations in elastic solids. But there must be a superior limit to the intensity, for intensities above which this relation will cease to hold. Viscosity, friction, and the little understood effects of permanent strain will make themselves more and more strongly felt as the strains increase beyond the limits of elasticity. I understand, indeed, that, in the case of cannon reports, the sound has been observed to travel somewhat less rapidly during its early than during its after stages. Here the very large initial aërial disturbances bring in conditions, either thermodynamic or elastic, under which the ordinary theory fails even in approximate application. If such a phenomenon is met with in the comparatively simple case of sound waves in air, similar phenomena are certain to exist in the more complex cases that correspond to earth shakings.

Another point, which this explicit recognition of purely elastic and *quasi*-elastic disturbances suggests, is in relation to the measurement of earthquake velocities by comparison of the effects at distant stations. Thus the purely elastic tremors felt at stations far distant from the centre of seismic disturbance have probably not come as such directly therefrom. They are, so to speak, the feebler descendants of the *quasi*-elastic disturbances, which may have caused havoc at localities

nearer to the seismic centre. The initial elastic tremors felt at these nearer stations will reach the further distant ones with intensities so diminished as no longer to be appreciable. Thus in the very usual method of timing the arrival of a tremor by the blurring of an image reflected from the surface of mercury, it is evident that the speed, as estimated between two stations in the line of propagation of the disturbance, must be somewhat smaller than the true value. For, before the particular tremors which sufficiently blurred the image at the first station have reached the second one, their intensity has become diminished. Hence the sufficient blurring of the image at the second station is due to the diminished violence of tremors, which passed through the first station subsequently to the blurring of the image there. Now the same reasoning will apply with even greater force to other than mere tremors; and especially will it apply to the case of the propagation of the quasi-elastic disturbances which constitute dangerous earthquakes.

If the views so far expressed are correct there is no difficulty in understanding the nature of earthquake sounds. As already pointed out, they are to be traced to rapid vertical vibrations of the ground, so rapid as to be inappreciable on our seismographs. Sometimes they may be due to transverse vibrations of walls caused by horizontal displacements of the ground; or, as suggisted by Mallet, they may be transmitted through the framework of the body. That these sounds should frequently precede the coming of the true earthquake shock is simply due to the running ahead of the purely elastic waves. The nature of the rock or soil through which these waves proceed will have a powerful influence upon their final intensity. Thus in soft rock, viscosity will soon destroy the vibrations of short period. In such circumstances there will be less chance of hearing earthquake sounds than when the rock is hard and solid. Very frequently earthquake sounds die away before the earth swayings have ceased—a fact which is probably connected with the short-lived character of the vertical

motion as compared with the horizontal motions traced out by our seismographs.

*With the air pulsations, which if rapid enough constitute audible sounds, the following curious effect of earthquakes may have some connection. I am indebted to Professor Sekiya for the information. It seems that, at the time an earthquake shock passes, or it may be a little sooner, birds flying in the air have been seen to drop suddenly, as if for an instant paralysed, and then to recover themselves. This effect might be sufficiently explained as due to a momentary mental paralysis produced by fear. Perhaps, however, we have a sufficient physical cause in the air pulsations, a slight change of density being enough to disturb the delicate poise of the hovering bird.

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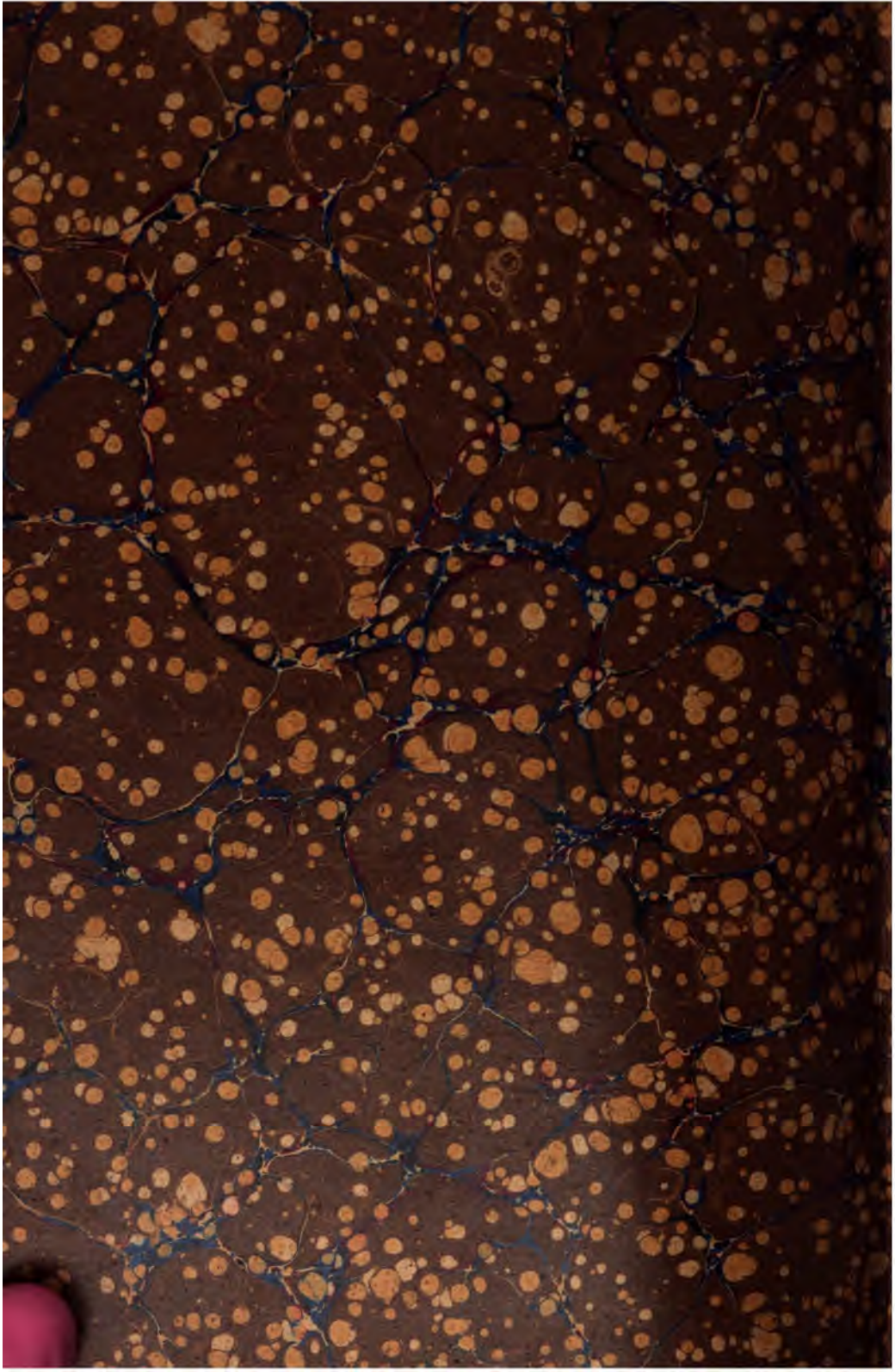

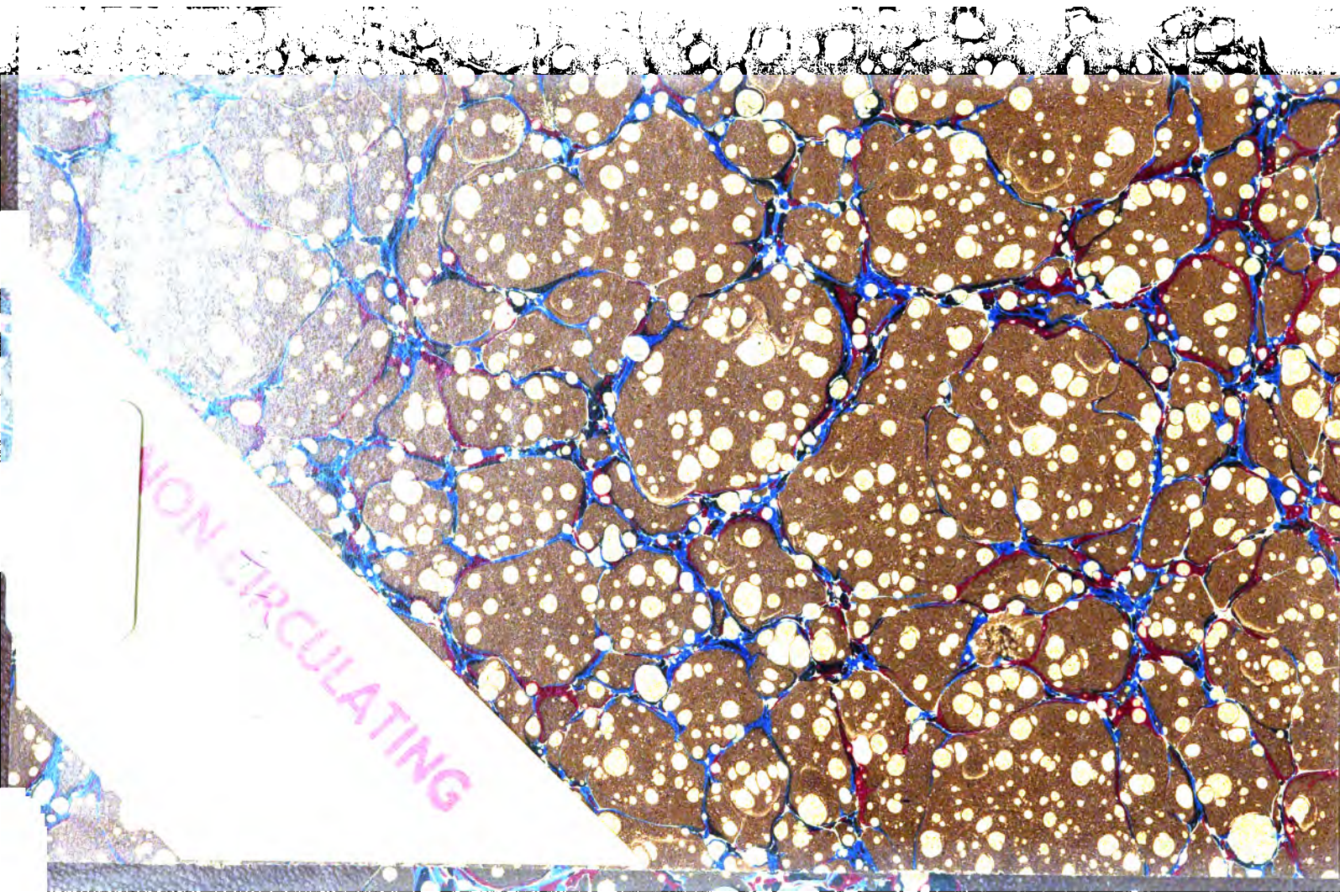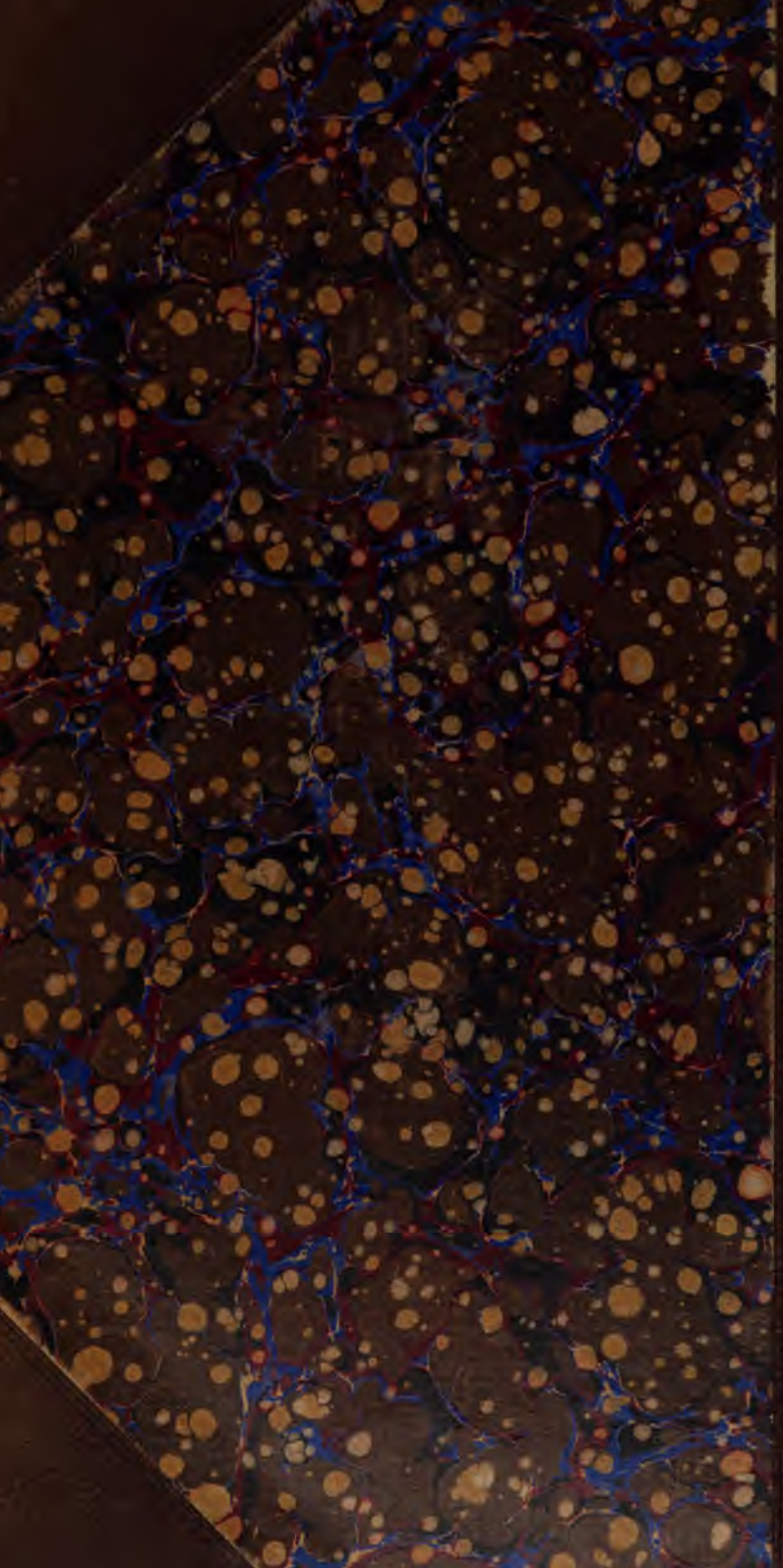
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